Fracture Characterization and SEM Examination of CC6 Mixes

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Contributions to one CC6 Objective

Investigate the relative effect of concrete strength on test item performance:

- Will concrete that is "too strong" perform poorly?
- Is the current flexural strength limitation in AC 150/5320-6E justified by objective full-scale test data?

Material (relative target flexural strength)	MRS1 (low)	MRS2 (medium)	MRS3 (high)
Target Strength (modulus of rupture), psi	500	750	1000
Harmony No. 57 Stone, Round, lbs	1550		
No. 57 Coarse Aggregate, lbs		1475	1535
No. 8 Intermediate Coarse Aggregate, lbs		490	535
Harmony Concrete Sand, lbs	1414		
Concrete Sand, lbs		1225	1070
Water, lbs	325	230	236
Type 1 Portland Cement, lbs	460	500	680
Air, %	6.5	7	4.5
Slump, in.	6	5.5	3.5
SIKAair, oz.	4.5	5	4.5
w/c Ratio	0.71	0.46	0.35

1N	2N	3N	4N*	5N	6N
20N	21N	22N	23N	24N	25N
1S	2S	3S	4S	5S	6S
20S	21S	22S	23S	24S	25S

MRS1: Low-Strength Mix

7N	8N	9N	10N	11N	12N	13N
26N	27N	28N	29N	30N	31N	32N
7S	8S	9S	10S	11S	12S	13S
26S	27S	28S	29S	30S	31S	32S

MRS2: Med-Strength Mix

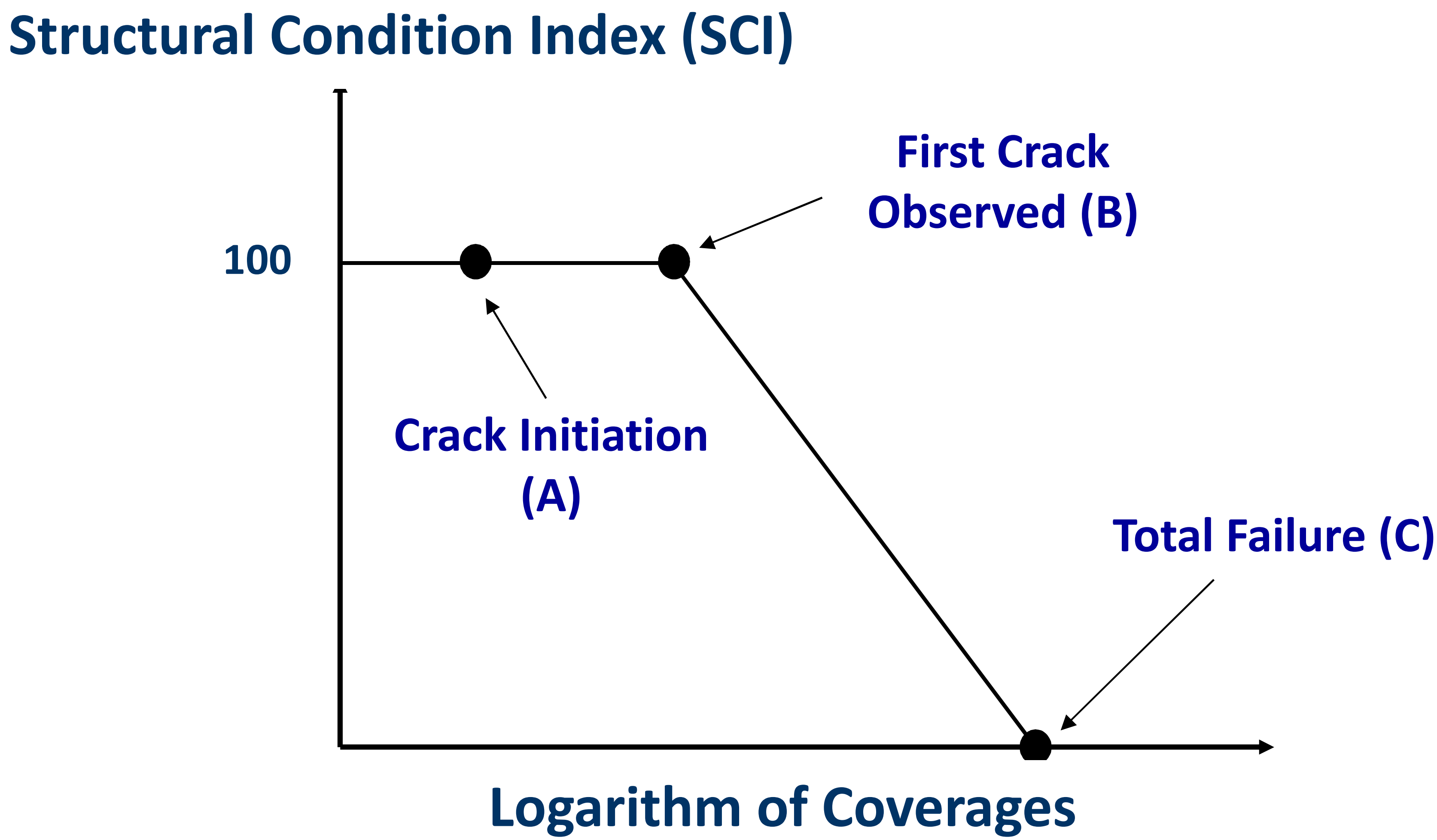
14N	15N	16N	17N	18N	19N
33N	34N	35N	36N	37N	38N
14S	15S	16S	17S	18S	19S
33S	34S	35S*	36S	37S	38S

MRS3: High-Strength Mix

Flexural Beam Fatigue Testing

- Initial testing of a limited number of cast beams at Penn State (MRS1)
- Remainder of fatigue testing conducted at NAPTF lab
- Beams sawn after full-scale loading completed

Fatigue Characterization



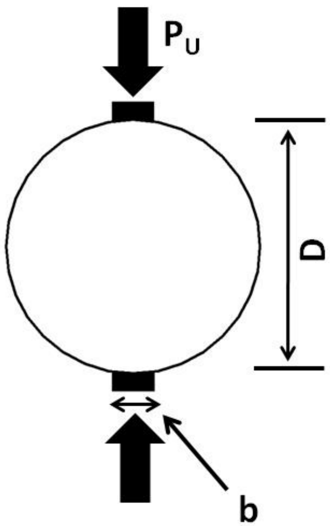
- Could material properties in addition to flexural strength improve the correlation to fatigue performance?

- Fracture energy has been suggested as showing promise for correlation to fatigue performance.

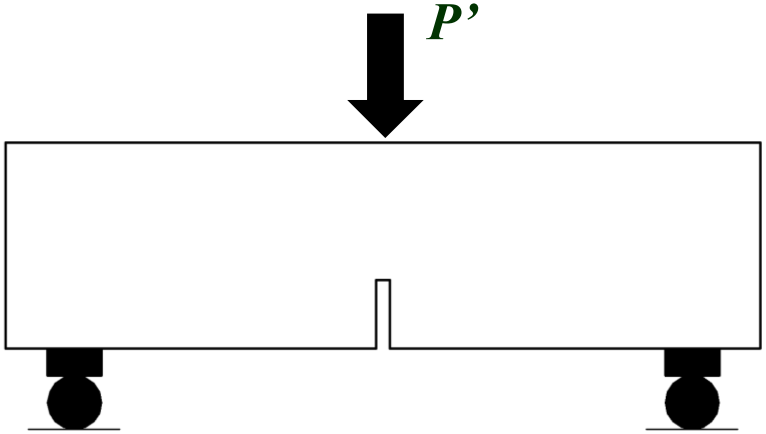
Test Specimens

- Fracture testing was performed on lab-cured beams formed in 2010 during CC6 construction
- FAA found strength losses in long-stored beams; cut cores and beams from the CC6 test items
- All specimens were kept in PSU wet curing chamber from arrival to testing:
  - 18 lab-cured cylinders and 18 lab-cured beams *(obtained June 2012; tested Aug-Sept 2012)*
  - 10 field-cut cores and 10 field-cut beams *(obtained November 2012; tested January 2013)*
  - 14 field-cut cores and 14 field-cut beams *(obtained March 2013; tested April and July 2013)*

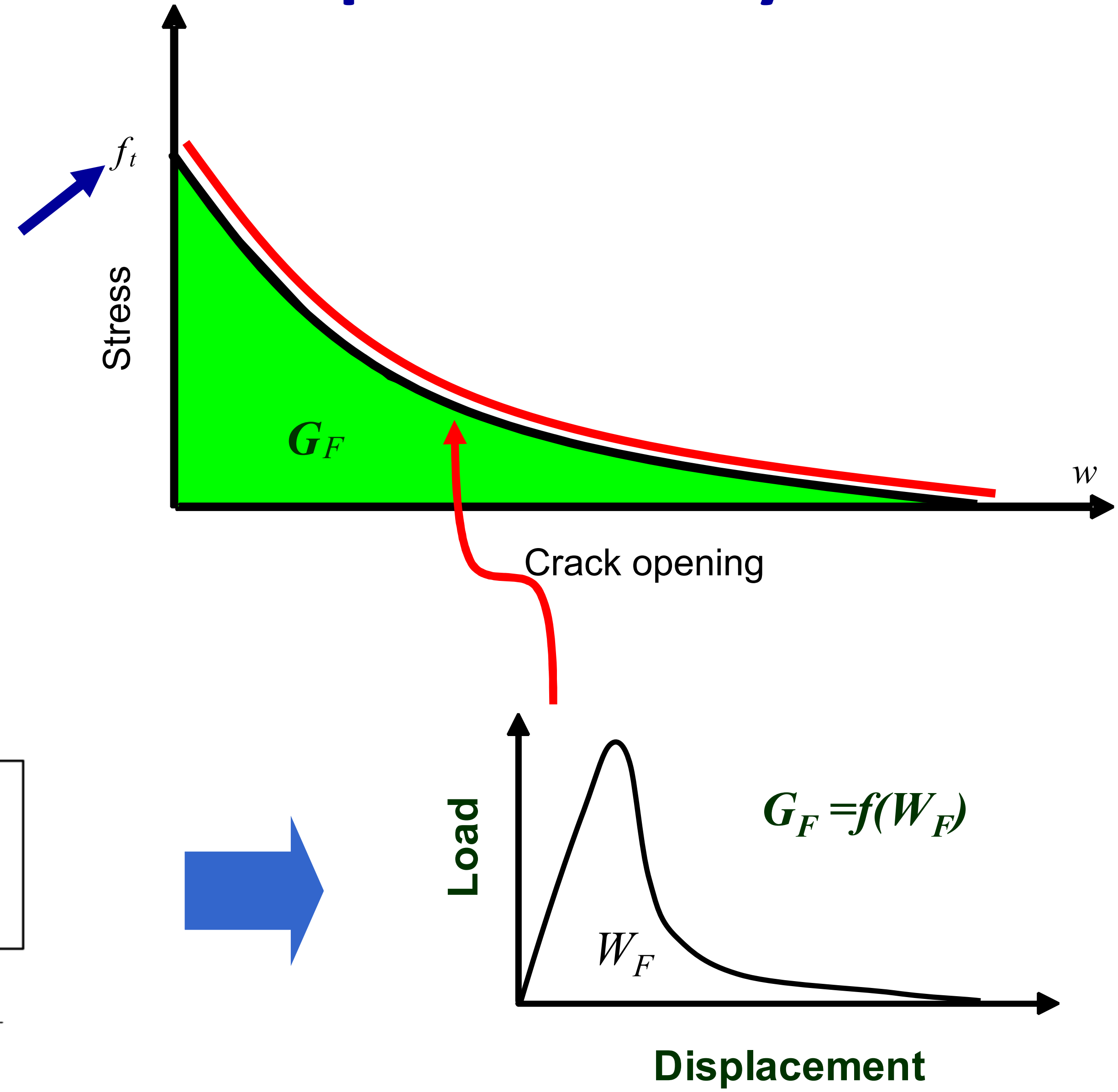
Fracture properties of concrete can be determined experimentally



Splitting Tensile Test



Three Point Bending Test

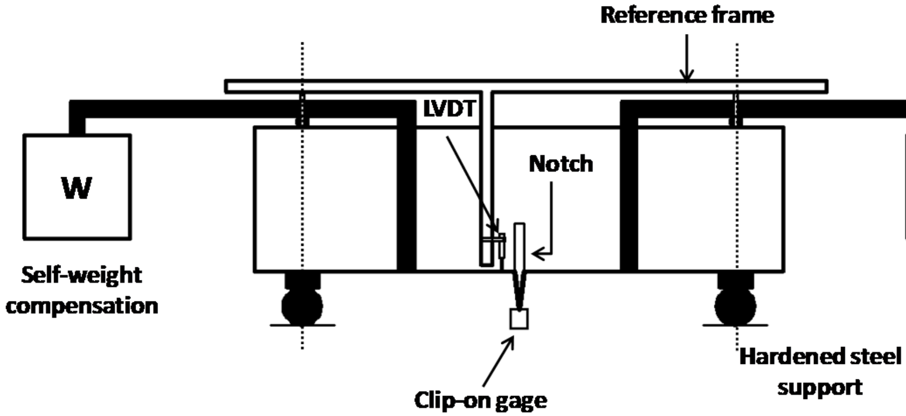


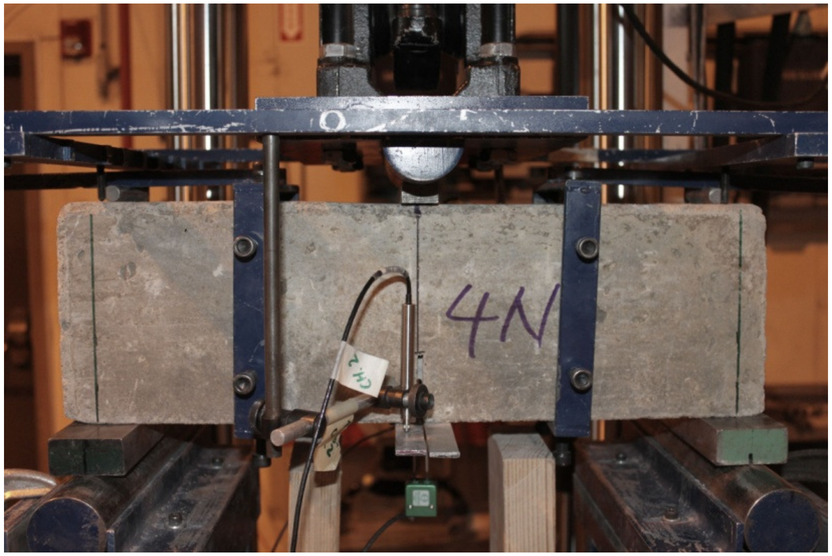
Split Tensile Test

Split Tensile Results

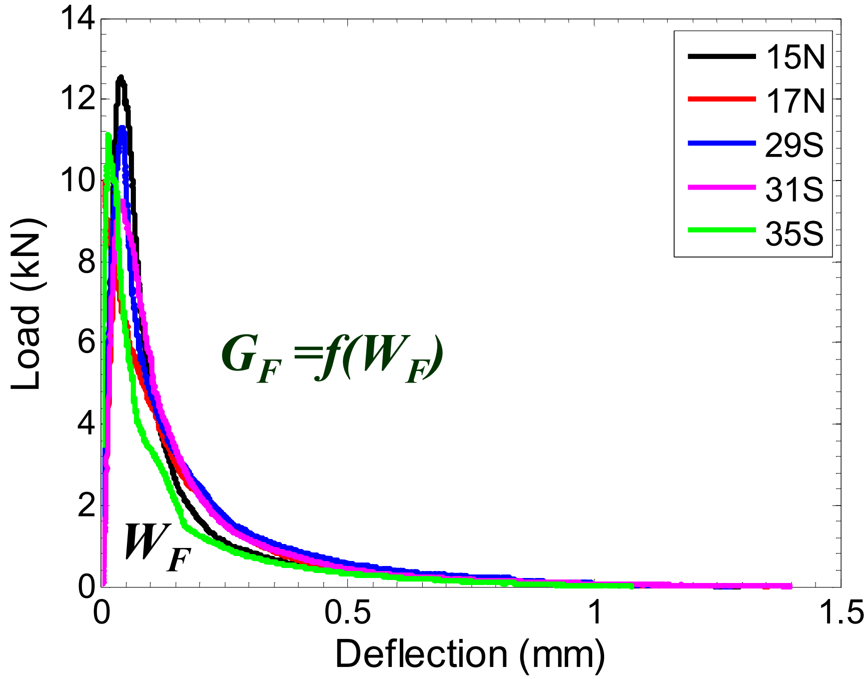
English	Design MOR	28 Day MOR	PSU Split Tensile	
			Lab-Cured	Field-Core
	(psi)	(psi)	(psi)	(psi)
MRS1	500	662	413	377
MRS2	750	763	434	377
MRS3	1000	1007	471	481
SI	Design MOR	28 Day MOR	PSU Split Tensile	
			Lab-Cured	Field-Core
	(MPa)	(MPa)	(MPa)	(MPa)
MRS1	3.45	4.56	2.85	2.60
MRS2	5.17	5.26	2.99	2.60
MRS3	6.89	6.94	3.25	3.32

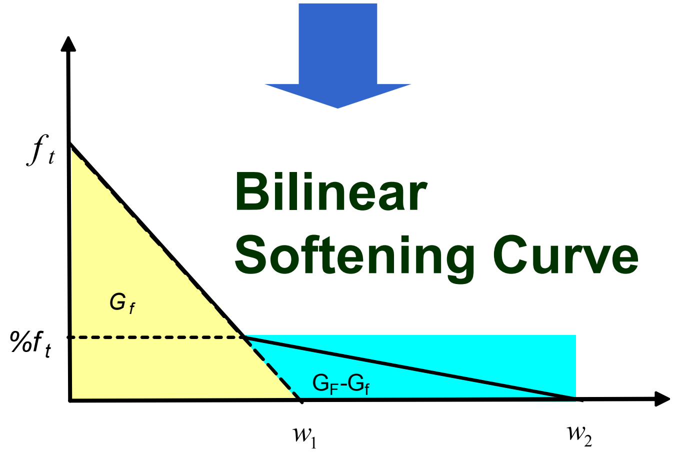
Closed-loop tests were used to determine the fracture energy





Three Point Bending Notched Specimens





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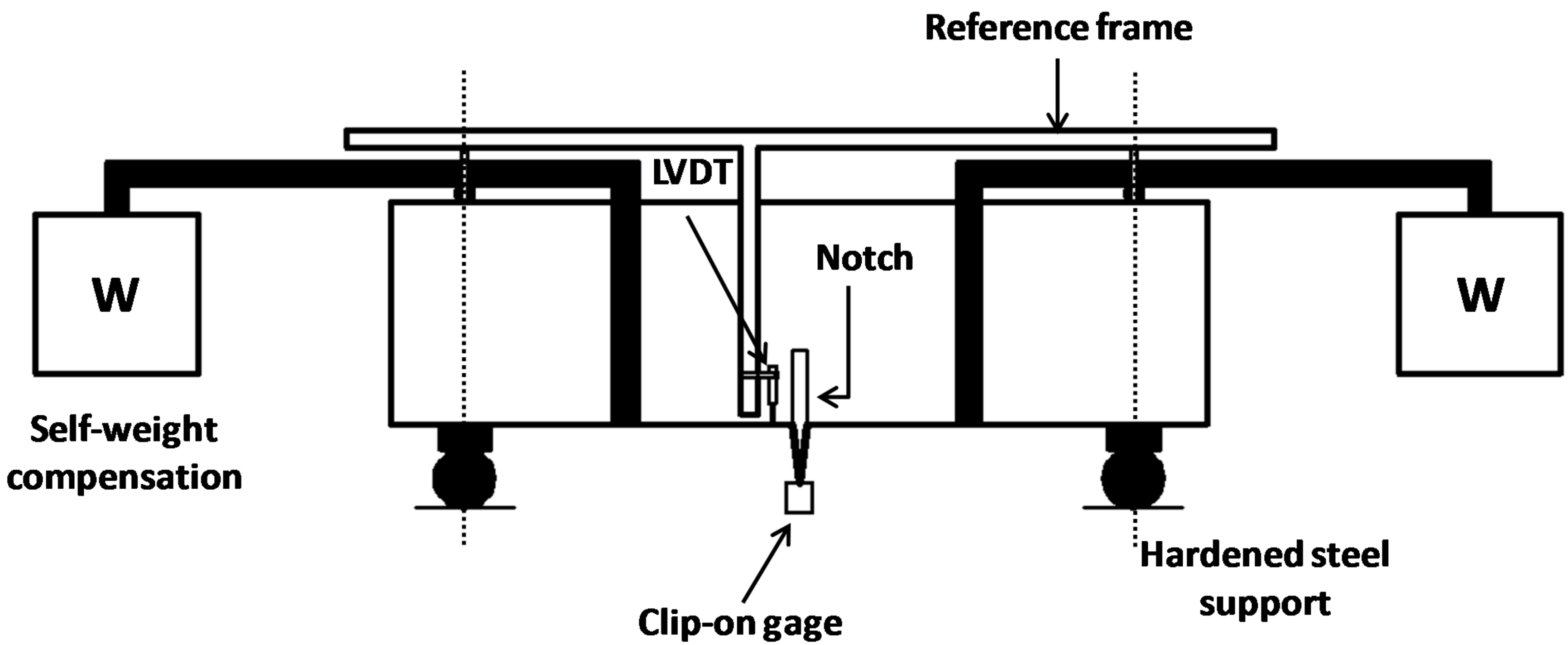
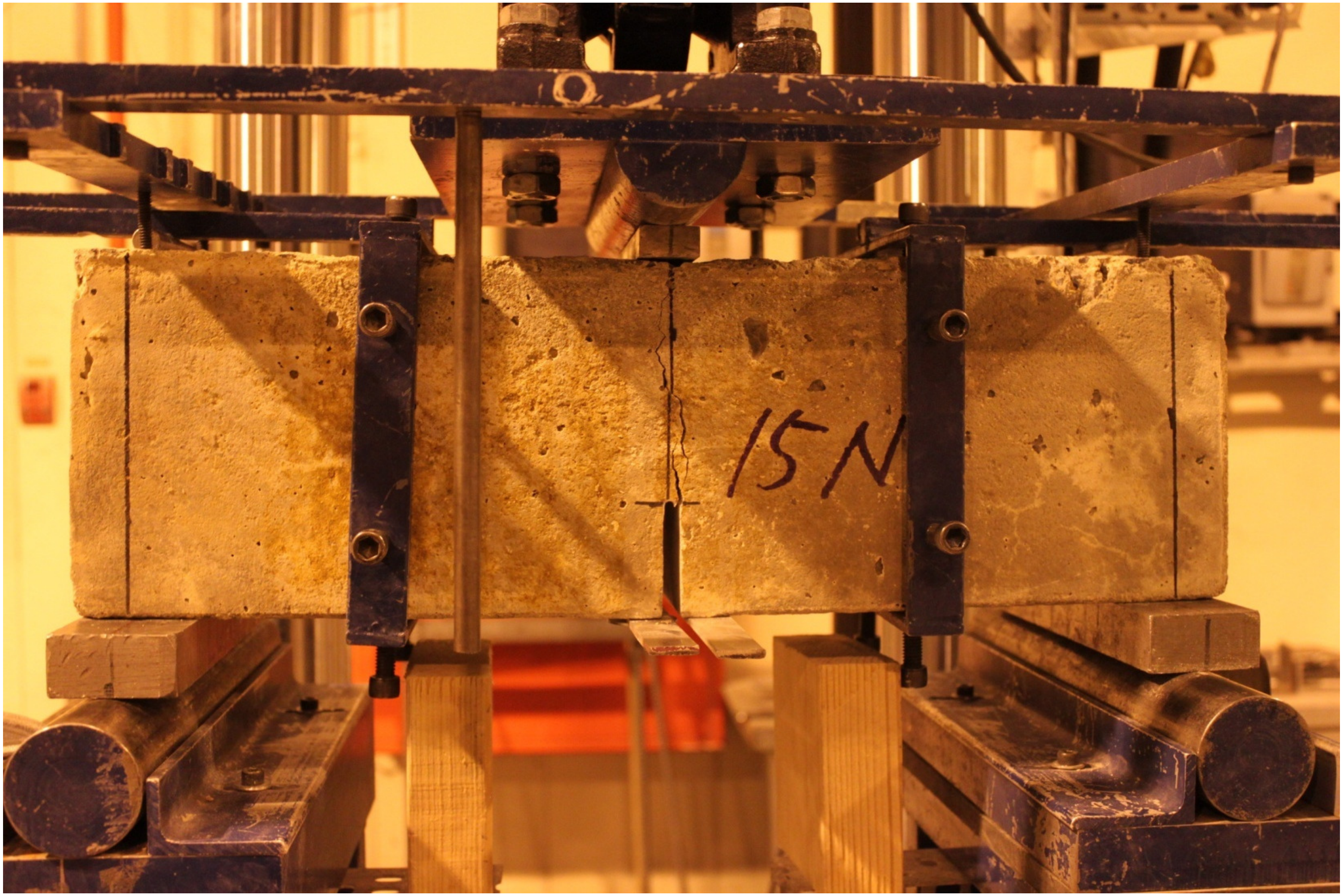
Fracture Testing
3-point bending tests of notched beams

- Protocol from American Concrete Institute, 2007
- Very similar to that used in Europe and published by RILEM
- All data recorded at 4 Hz
- Typical test durations were 210 minutes
- Peak load reached in less than 5 minutes

Three Point Bending Schematic



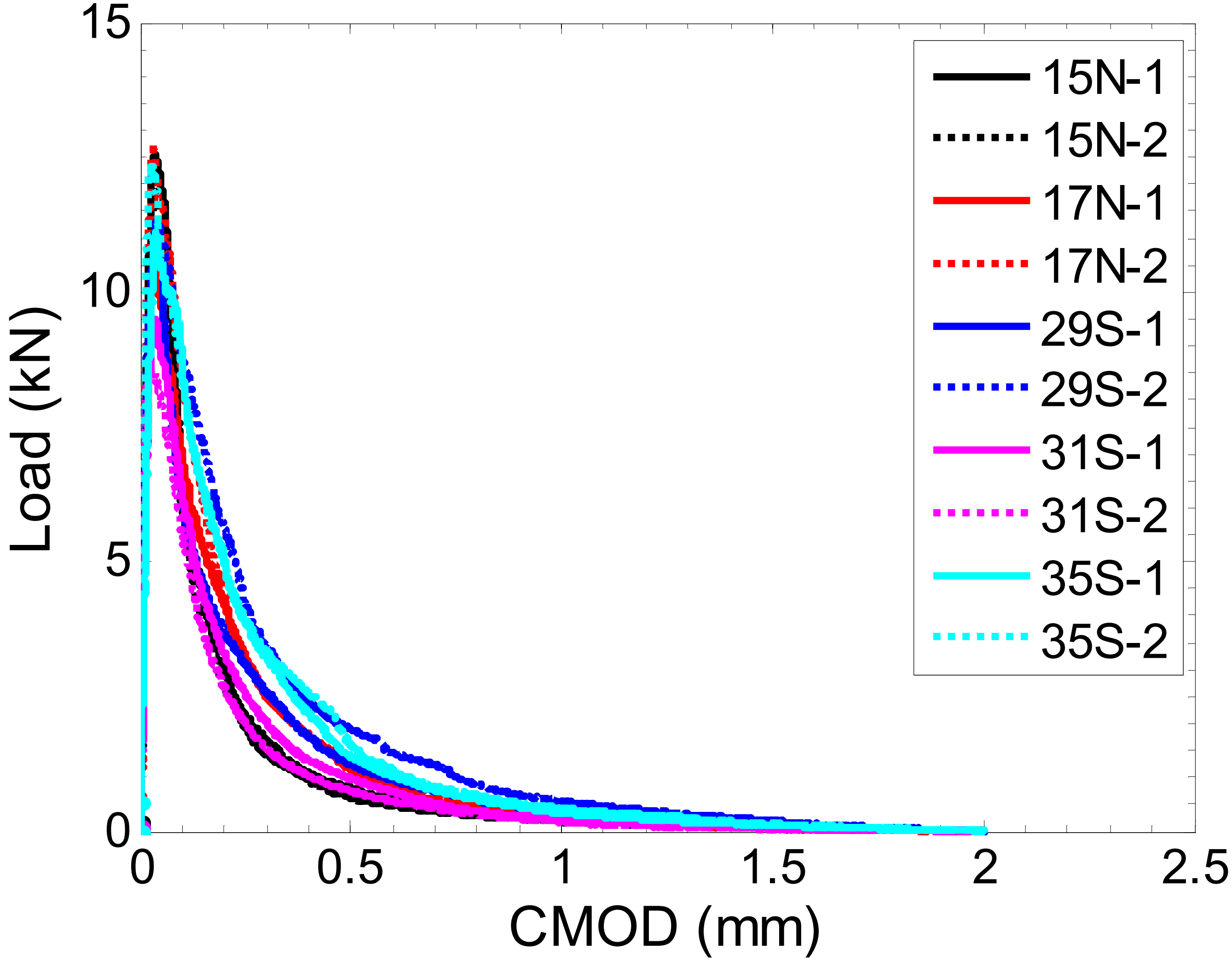
Three Point Bending Test



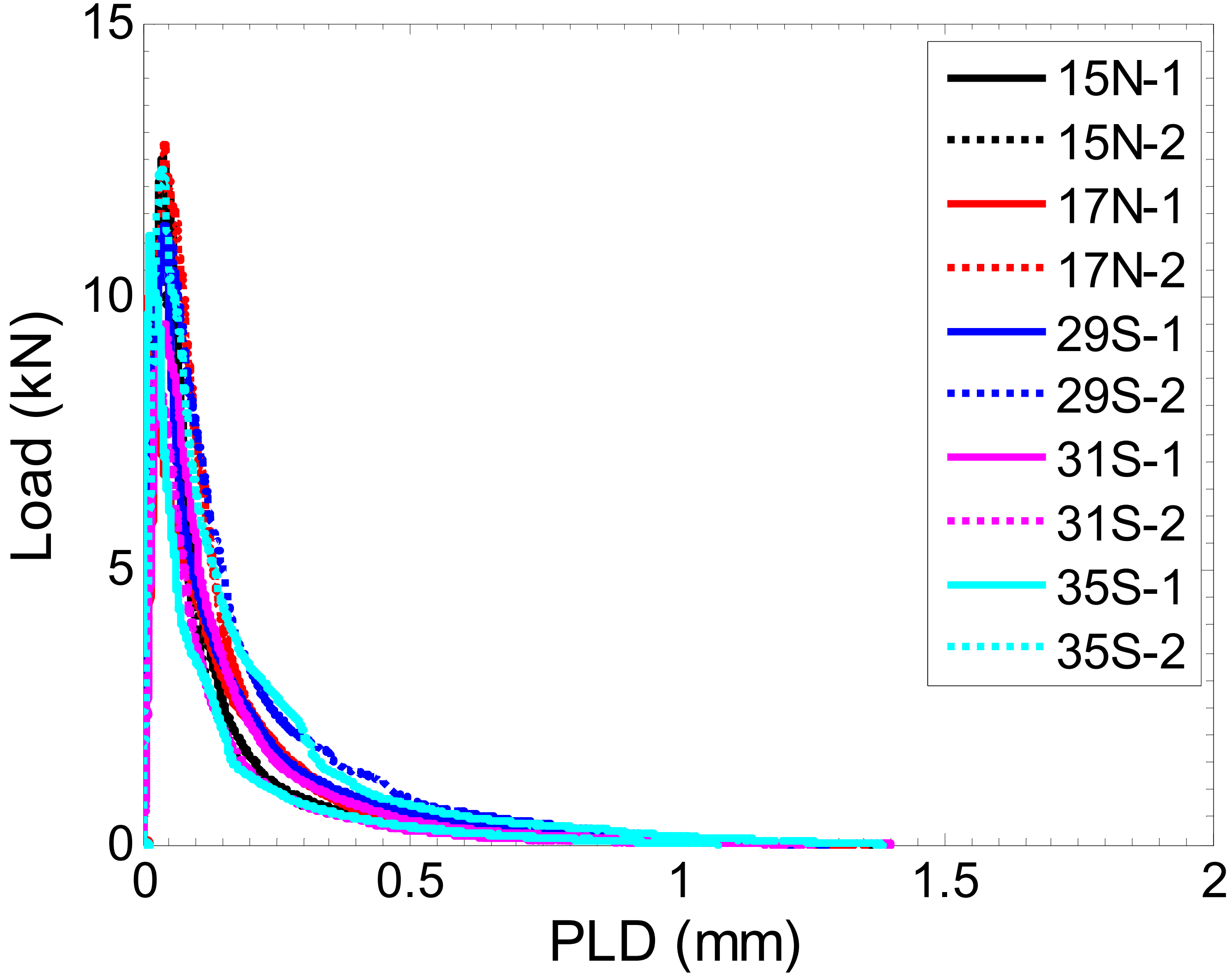
Three Point Bending Test Controlled Variables

Closed-loop Control Used in Three Point Bending Test			
	Control Variable	Rate	Ending point
Step 1	Load	0.5 kN/min	1 kN
Step 2	CMOD	0.01 mm/min	2 mm
Step 3	Displacement	0.1 mm/min	4 mm

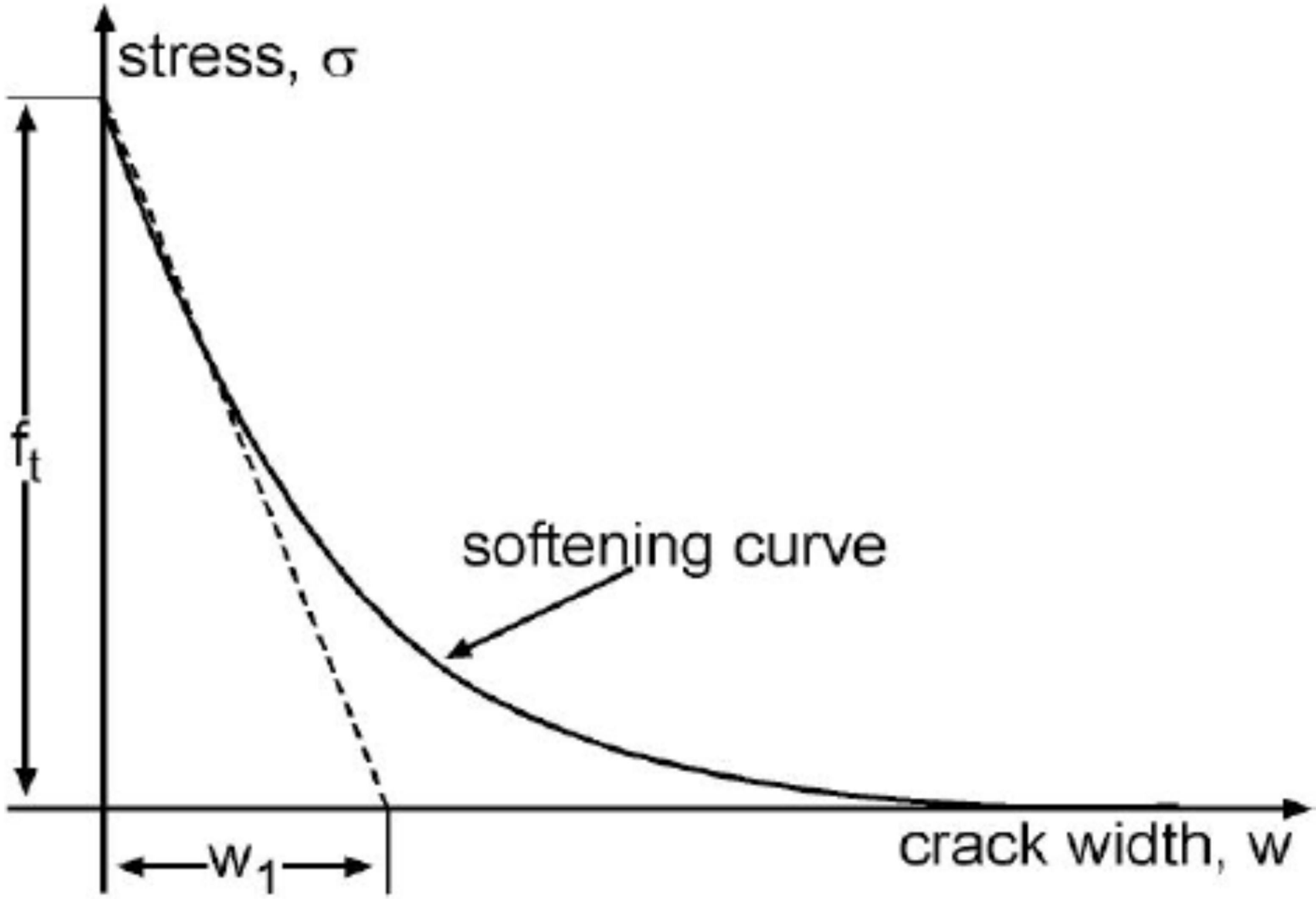
Three Point Bending Test
Load vs. CMOD



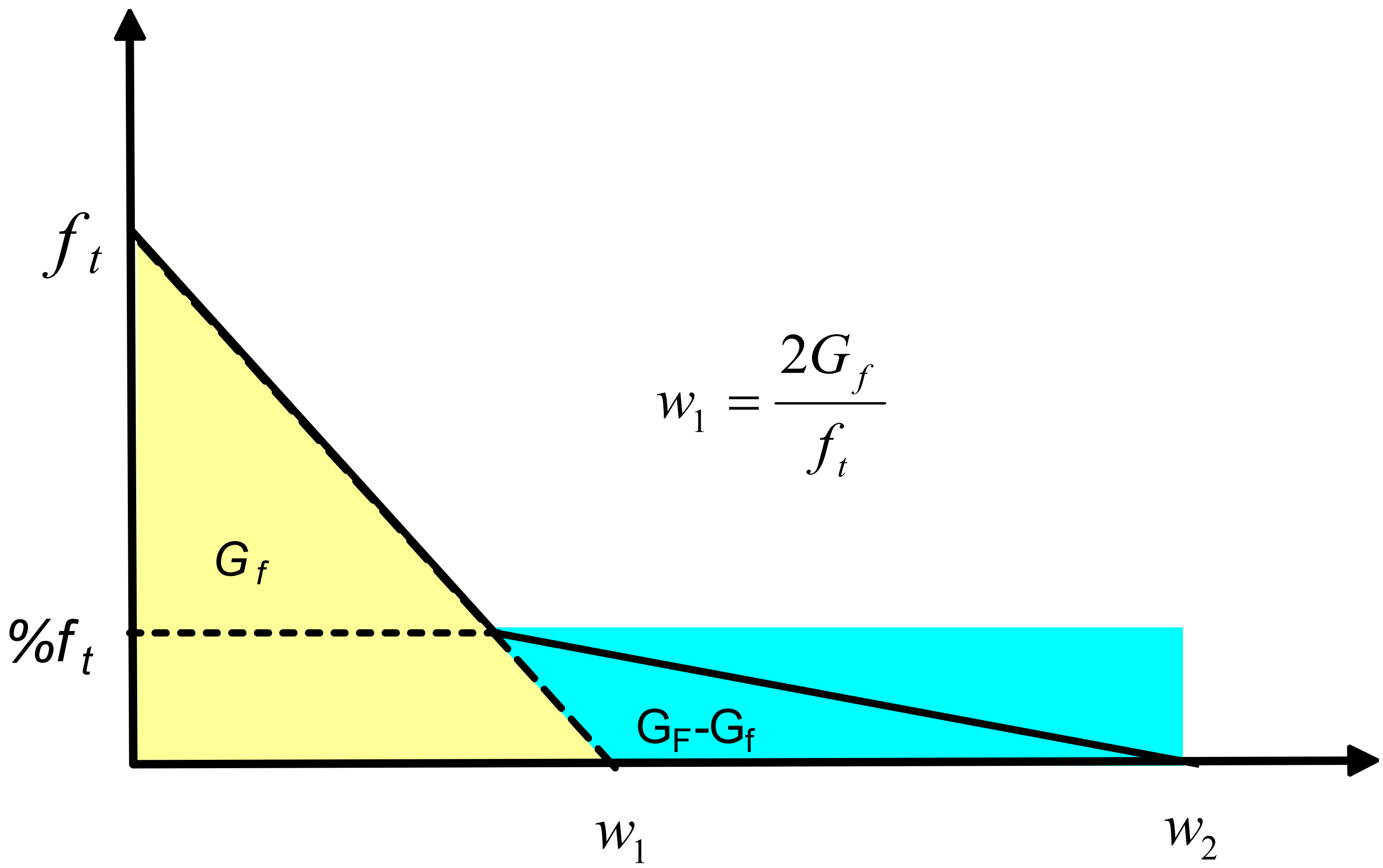
Three Point Bending Test
Load vs. Plate Load Deflection



Stress vs. Crack Opening Curve



Fracture Energy



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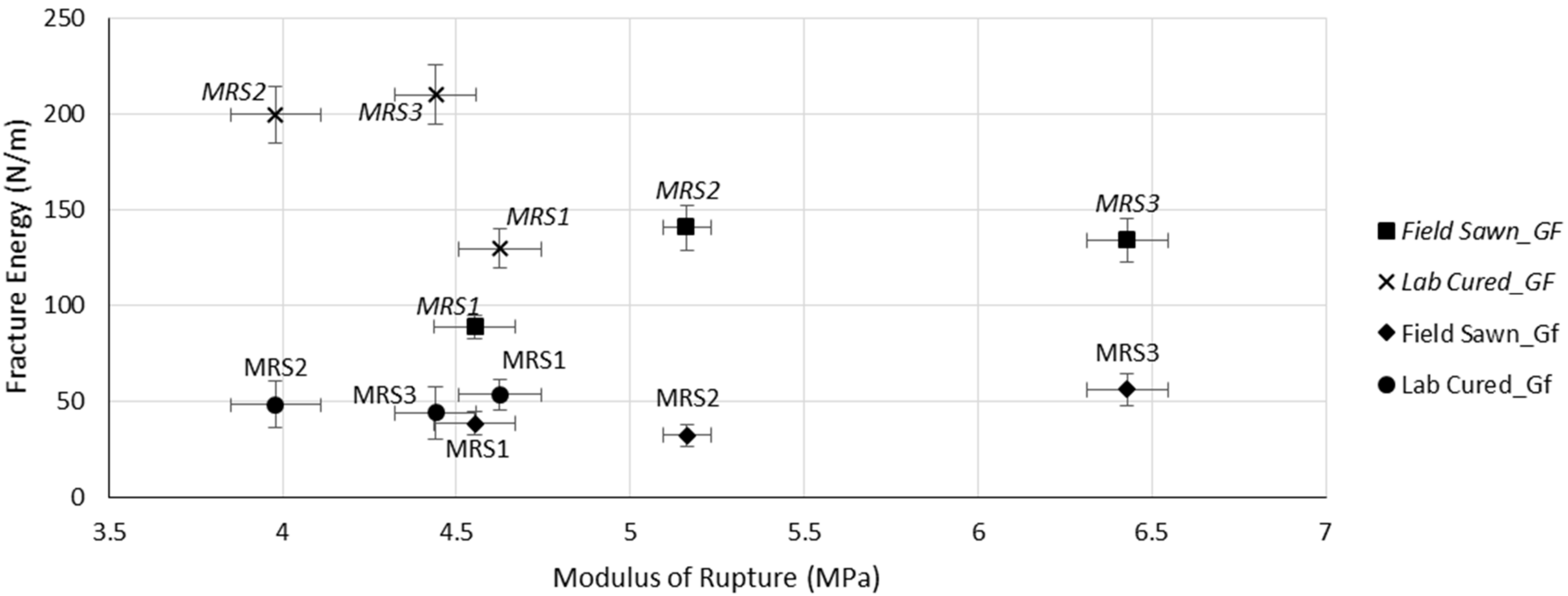
Average Fracture Energy Values

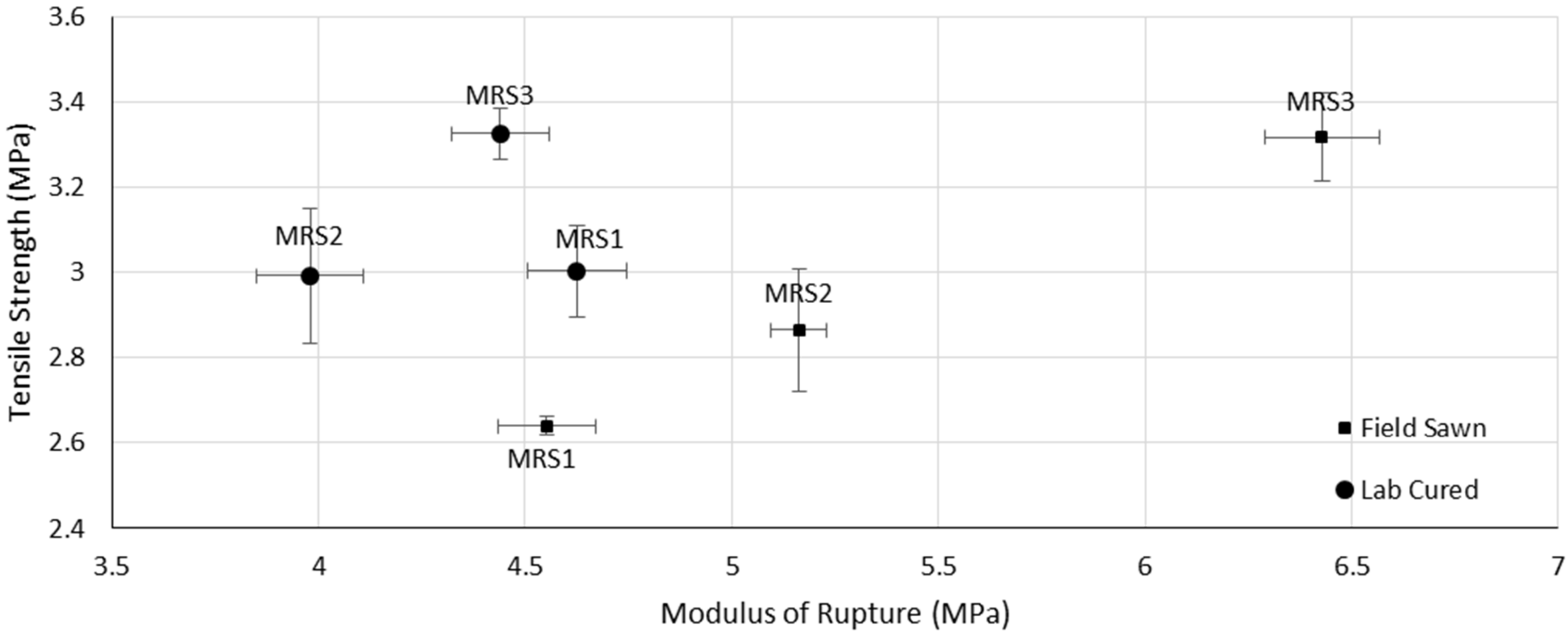
SI	Lab Cured		Field Sawn	
	Total Fracture Energy	Size Effect Fracture Energy	Total Fracture Energy	Size Effect Fracture Energy
	(N/m)	(N/m)	(N/m)	(N/m)
MRS1	129.7	51.3	88.9	36.0
MRS2	199.8	45.0	140.9	32.5
MRS3	210.3	44.0	134.1	56.2

Fracture Energy vs. Modulus of Rupture



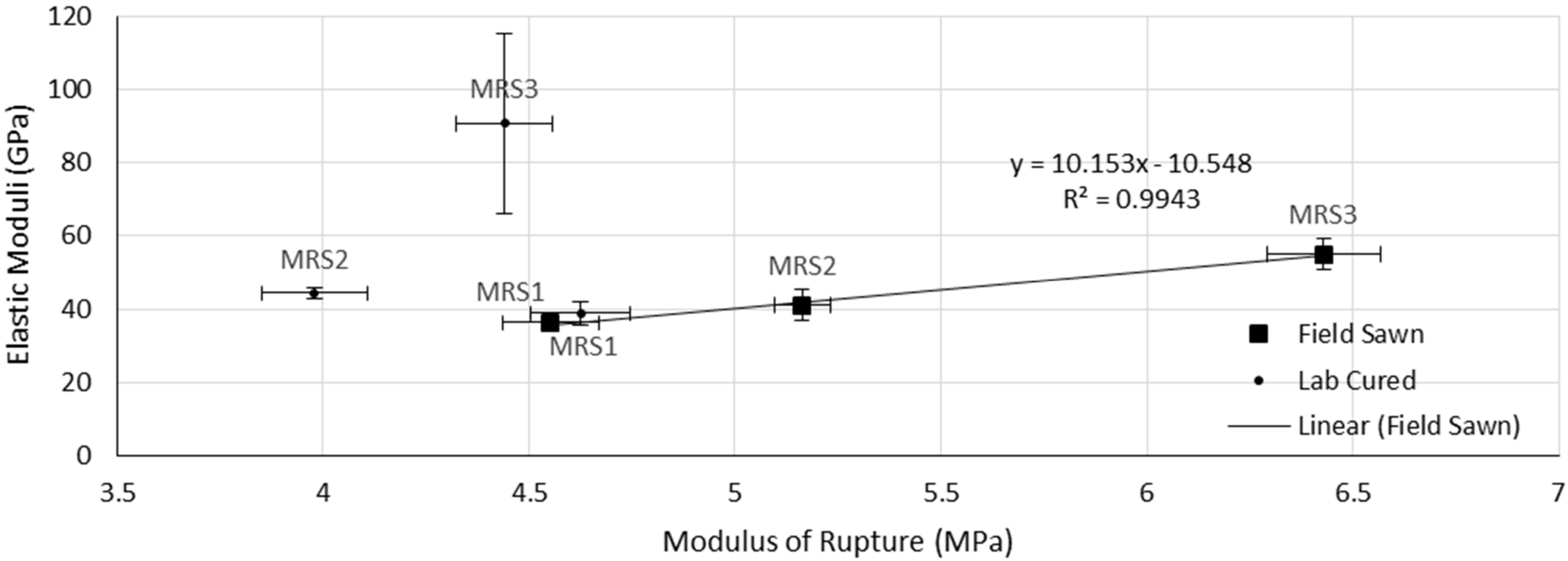
* Error bars indicate standard errors

Split Tensile Strength versus Modulus of Rupture



* Error bars indicate standard errors

Elastic Modulus versus Modulus of Rupture



* Error bars indicate standard errors

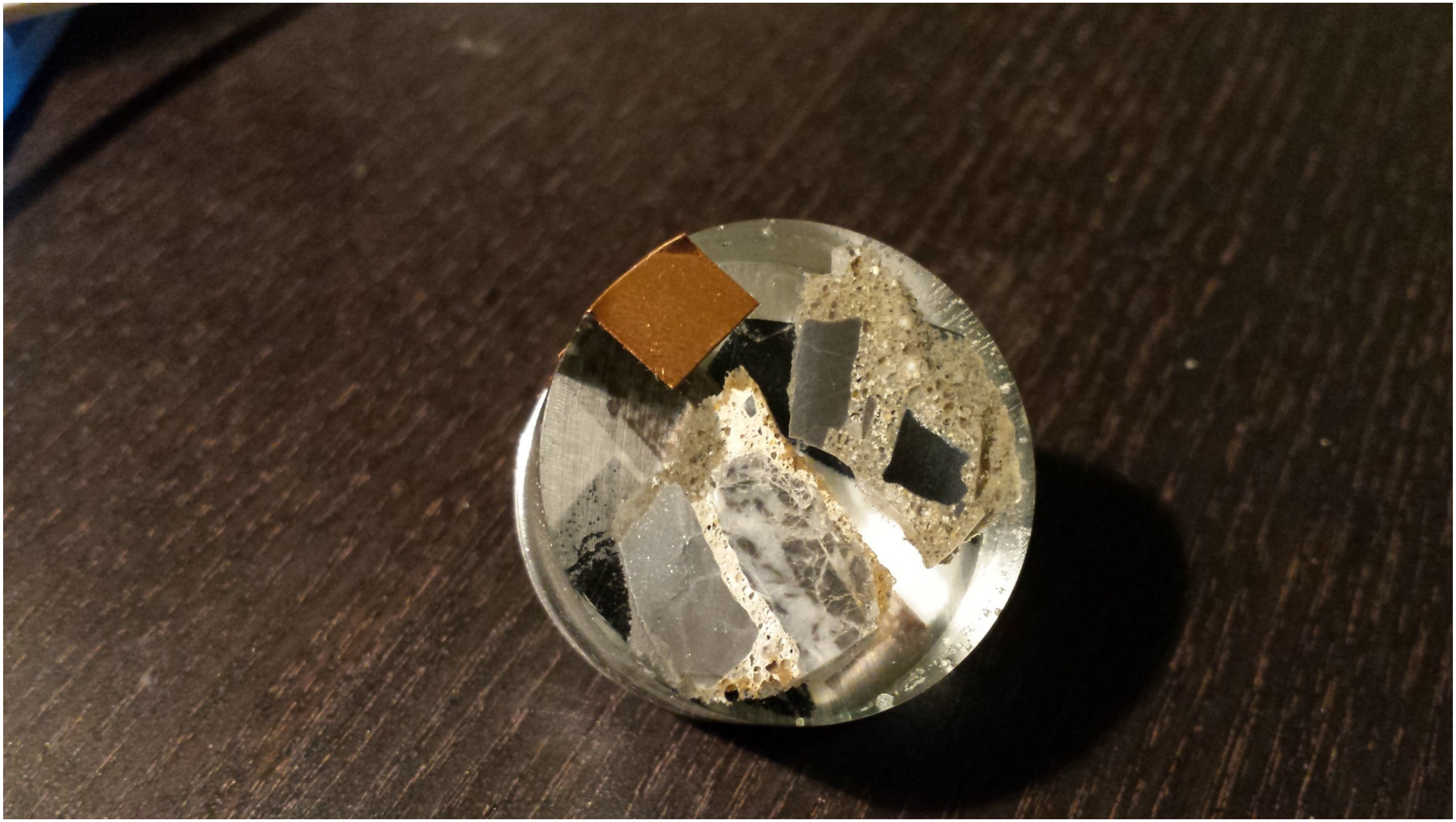
Microscopic Examination

- Scanning Electron Microscopy (SEM)
  - Performed using FEI Quanta 200 Environmental SEM
  - Examination of microstructure
  - Possible cause(s) of strength loss with long-term storage
- Energy-dispersive X-ray Spectroscopy (EDS)
  - Examination of chemical composition of microscopic features

Macroscopic Examination

Prepared SEM Specimens

Prepared SEM Specimen



Prepared SEM Specimen

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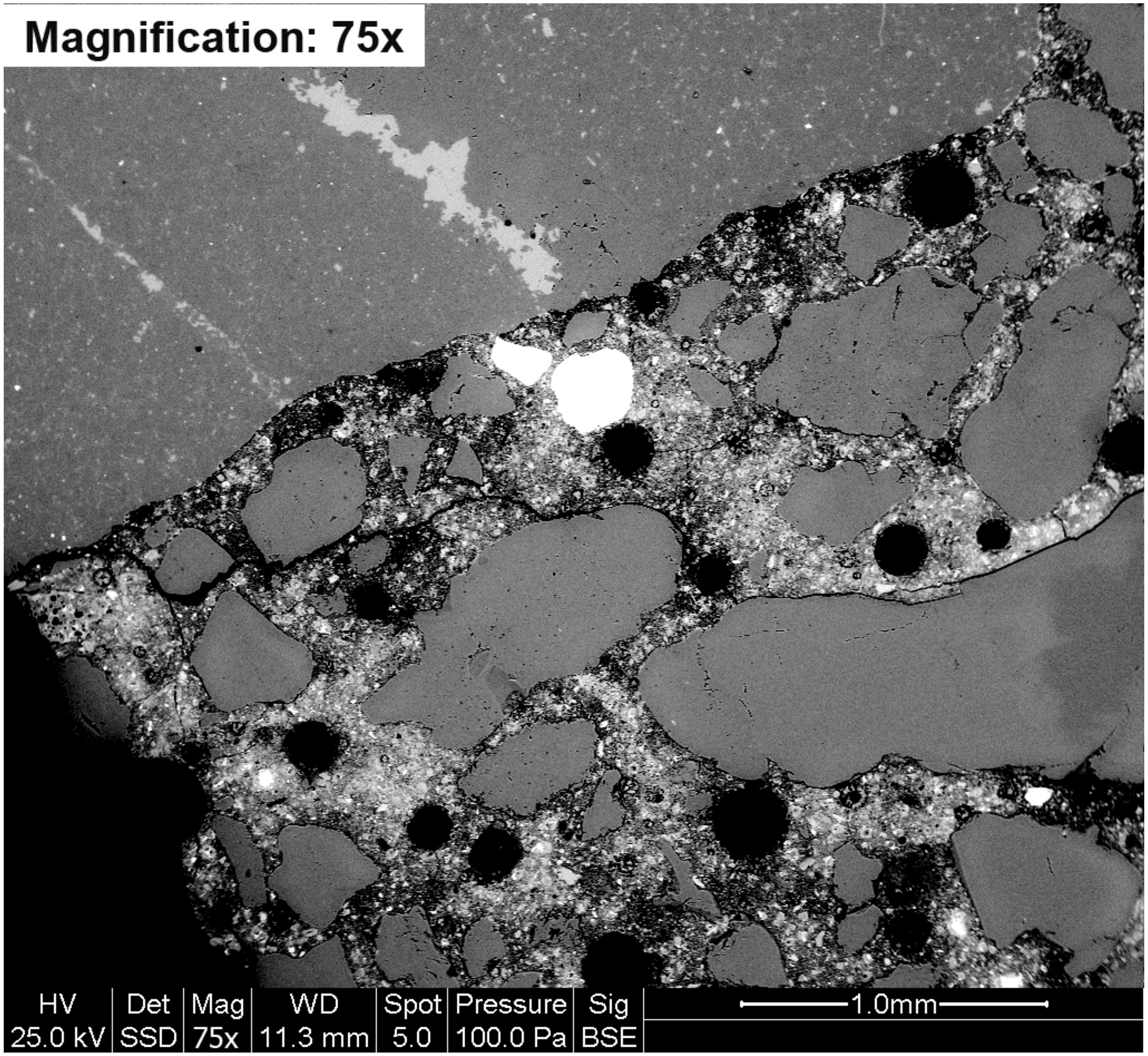
29S (MRS2) Field-Sawn Specimen



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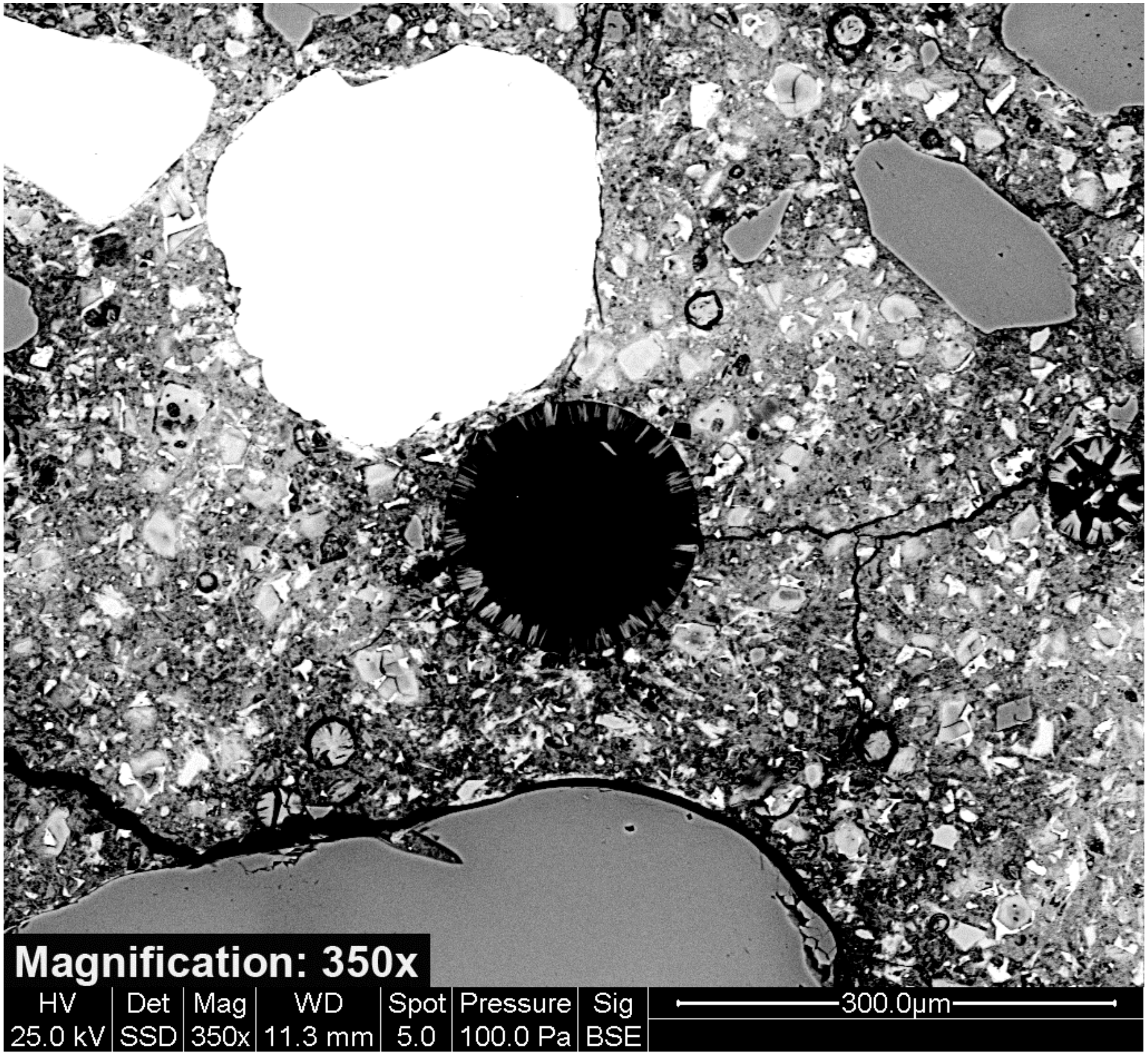
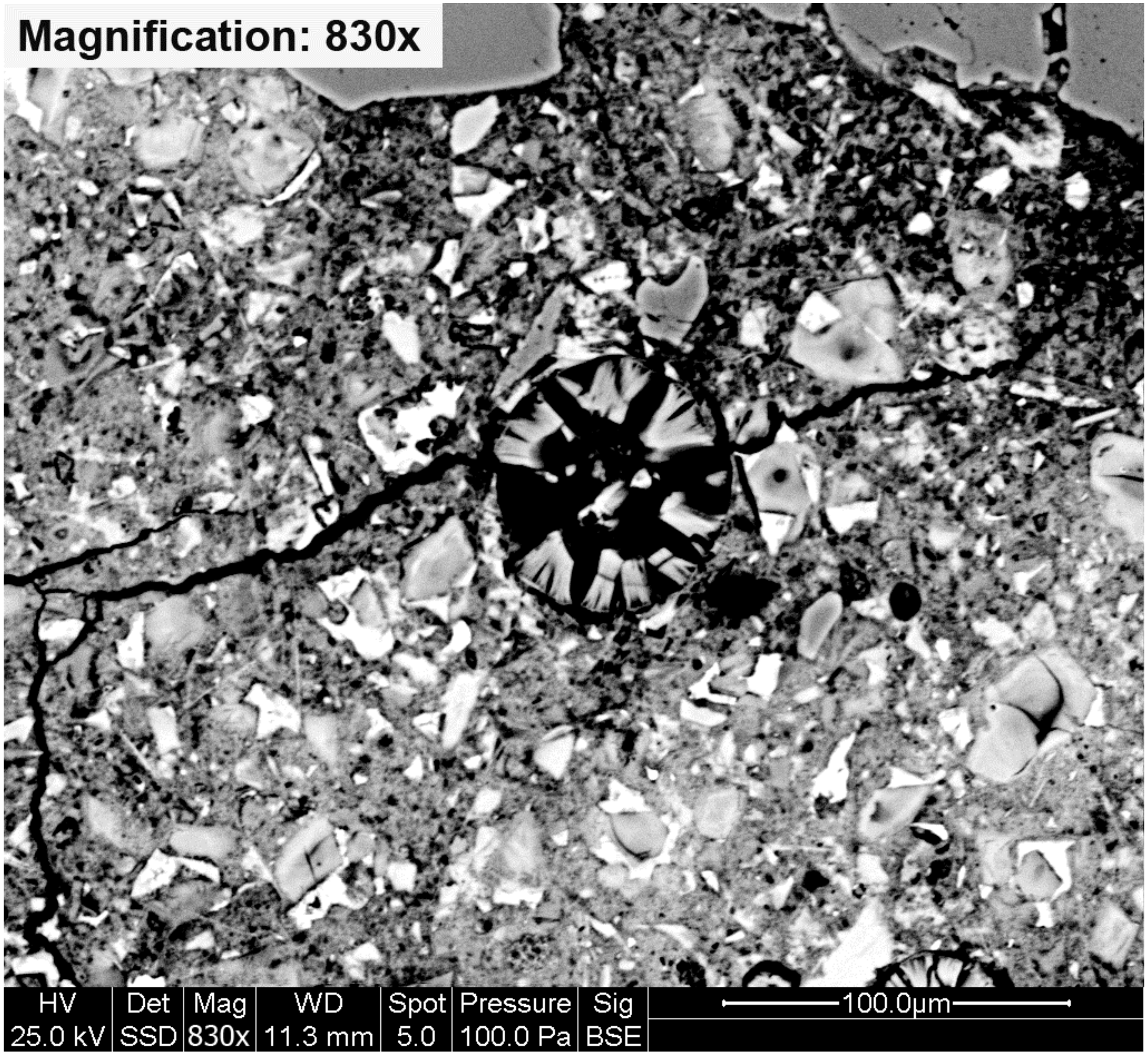
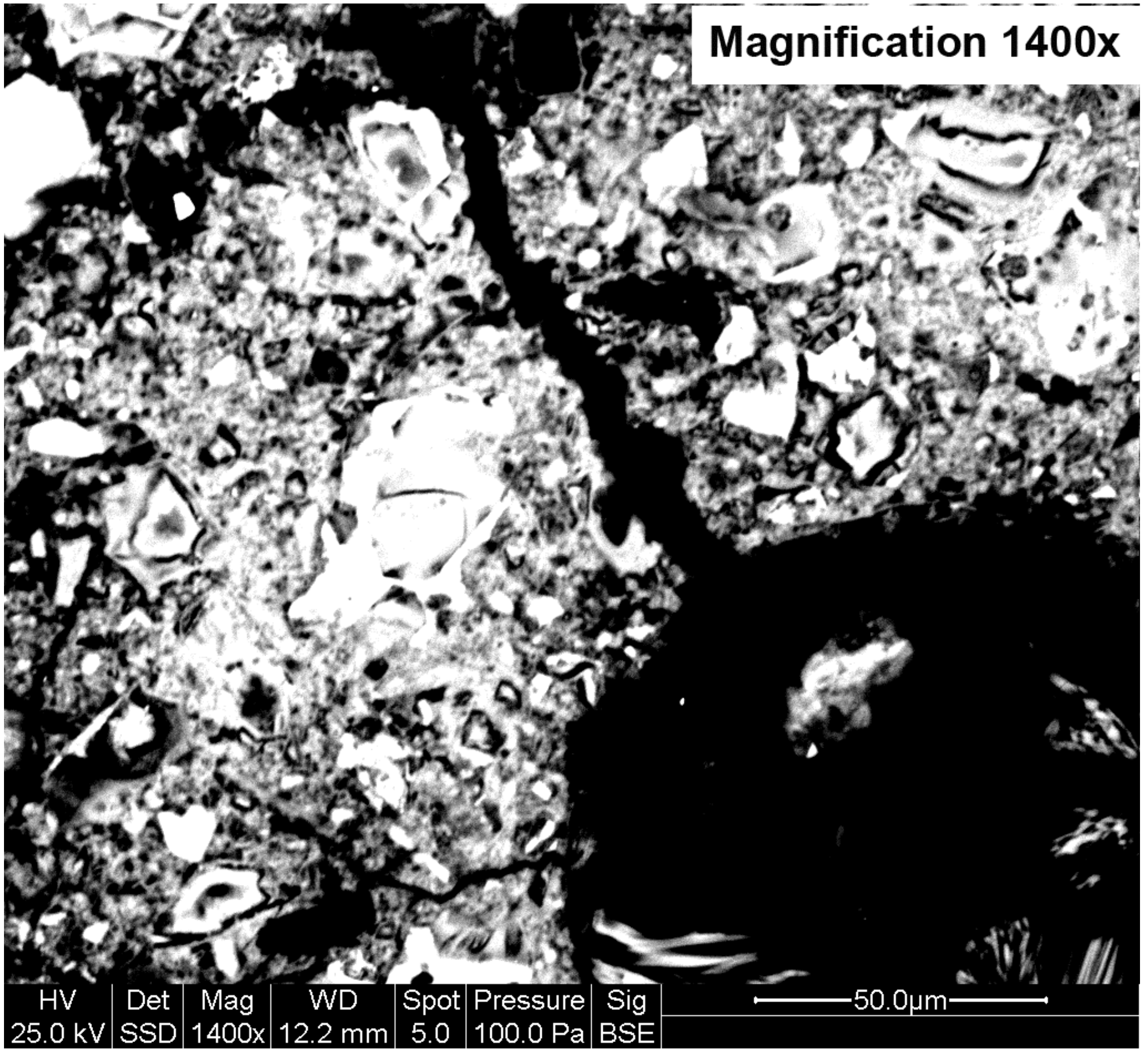
29S (MRS2) Field-Sawn Specimen



29S (MRS2) Field-Sawn Specimen



29N (MRS2) Lab-Cured Specimen



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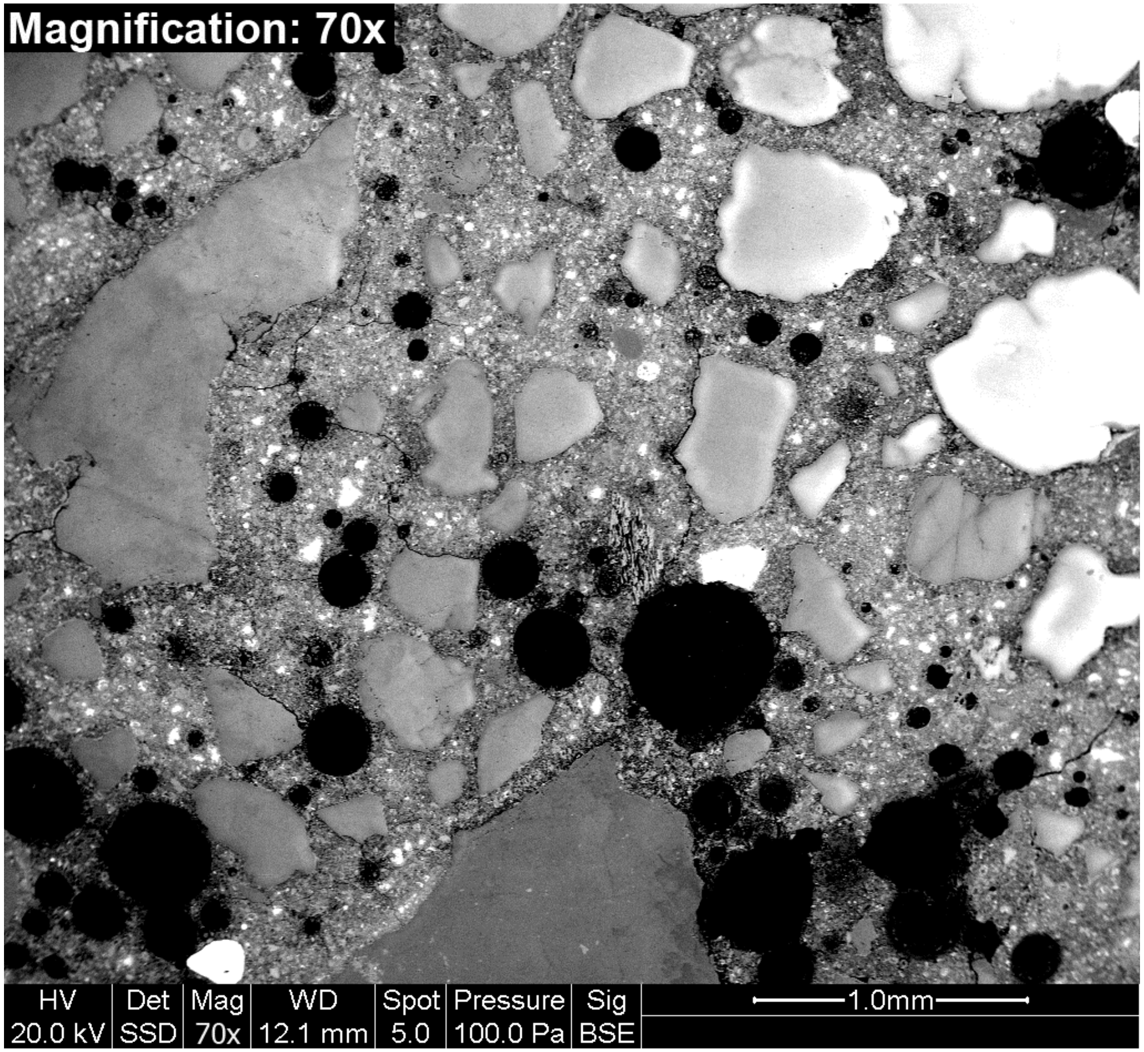
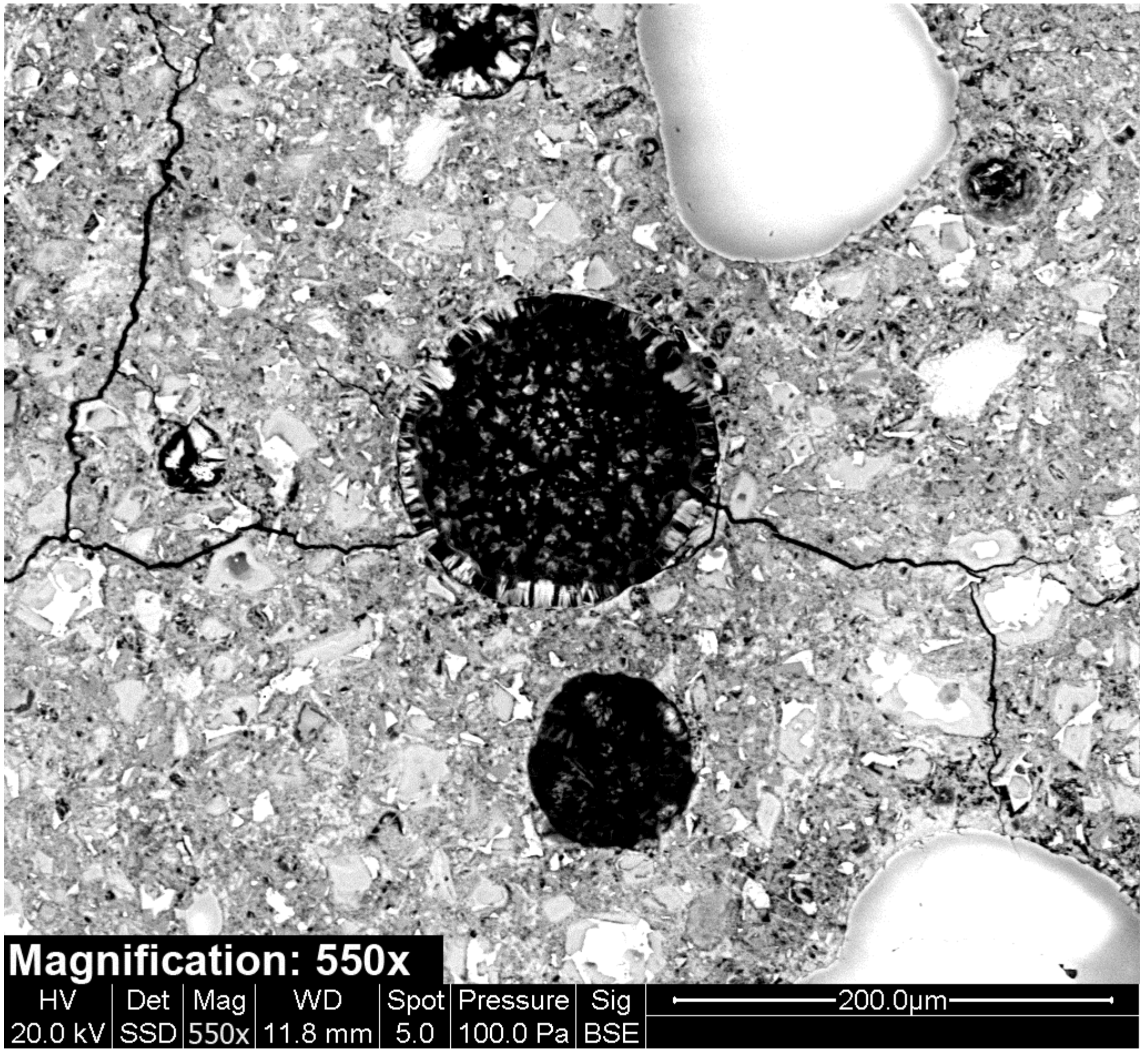
29N (MRS2) Lab-Cured Specimen

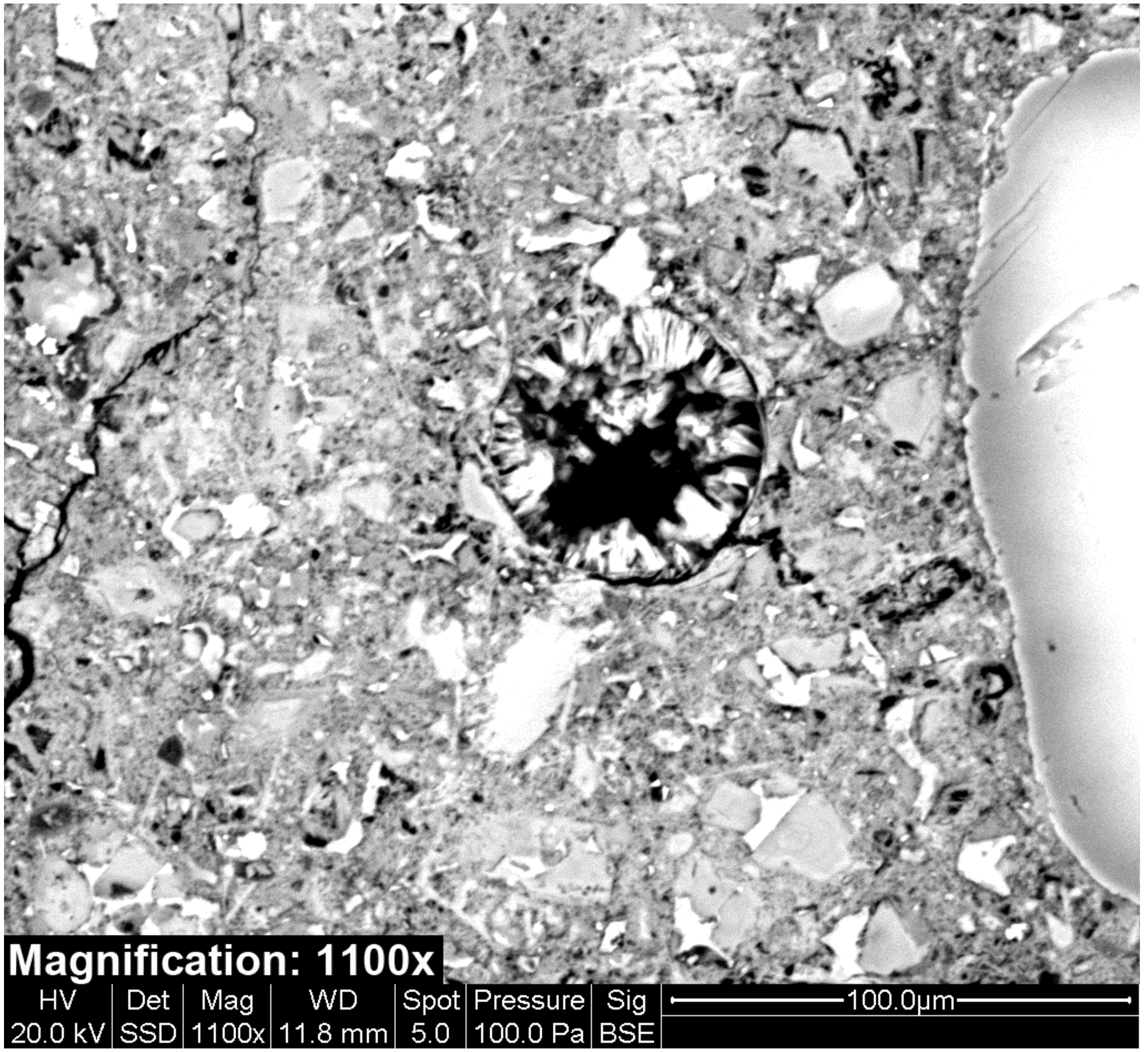
15N (MRS3) Field-Sawn Specimen



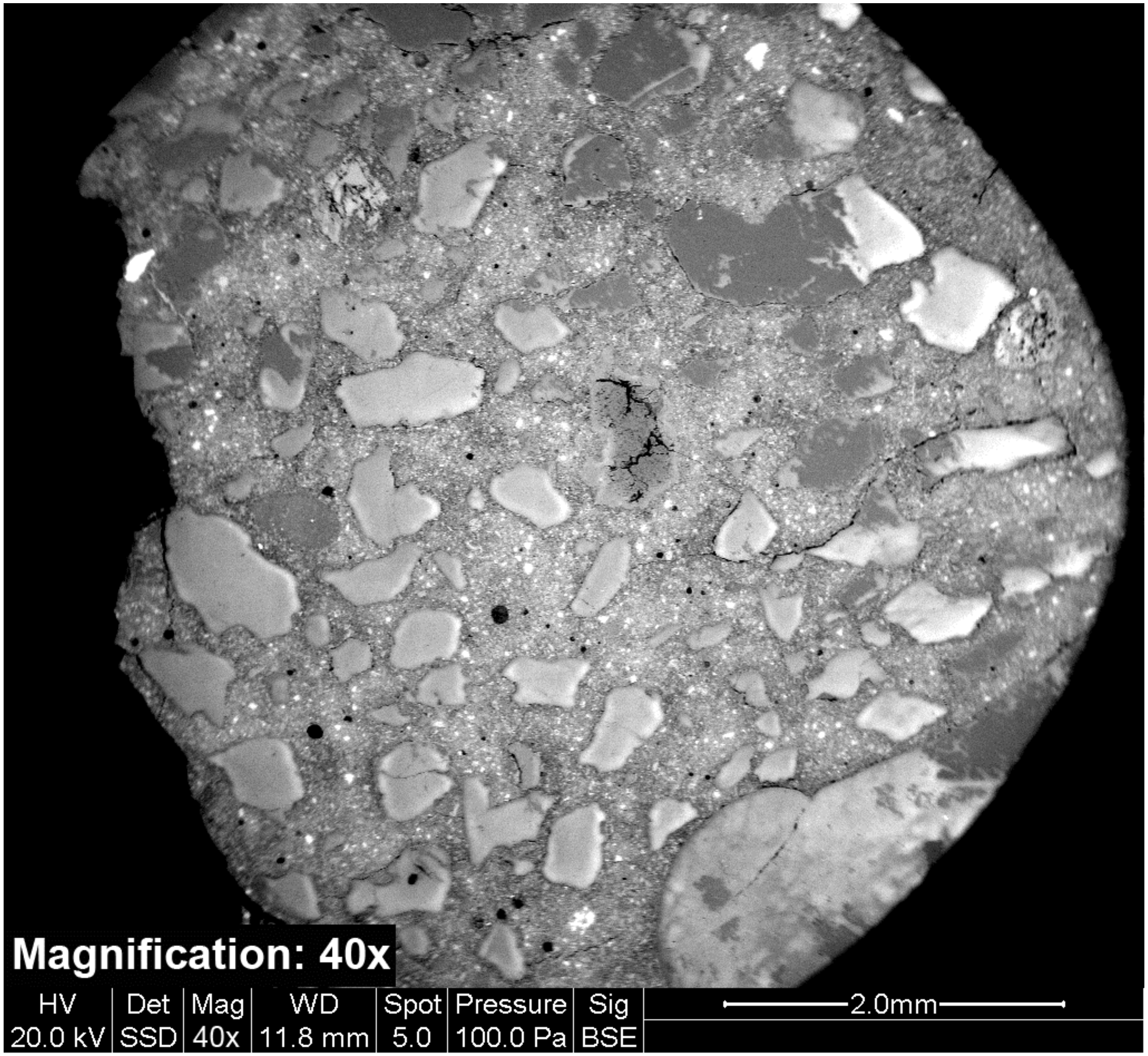
15N (MRS3) Field-Sawn Specimen



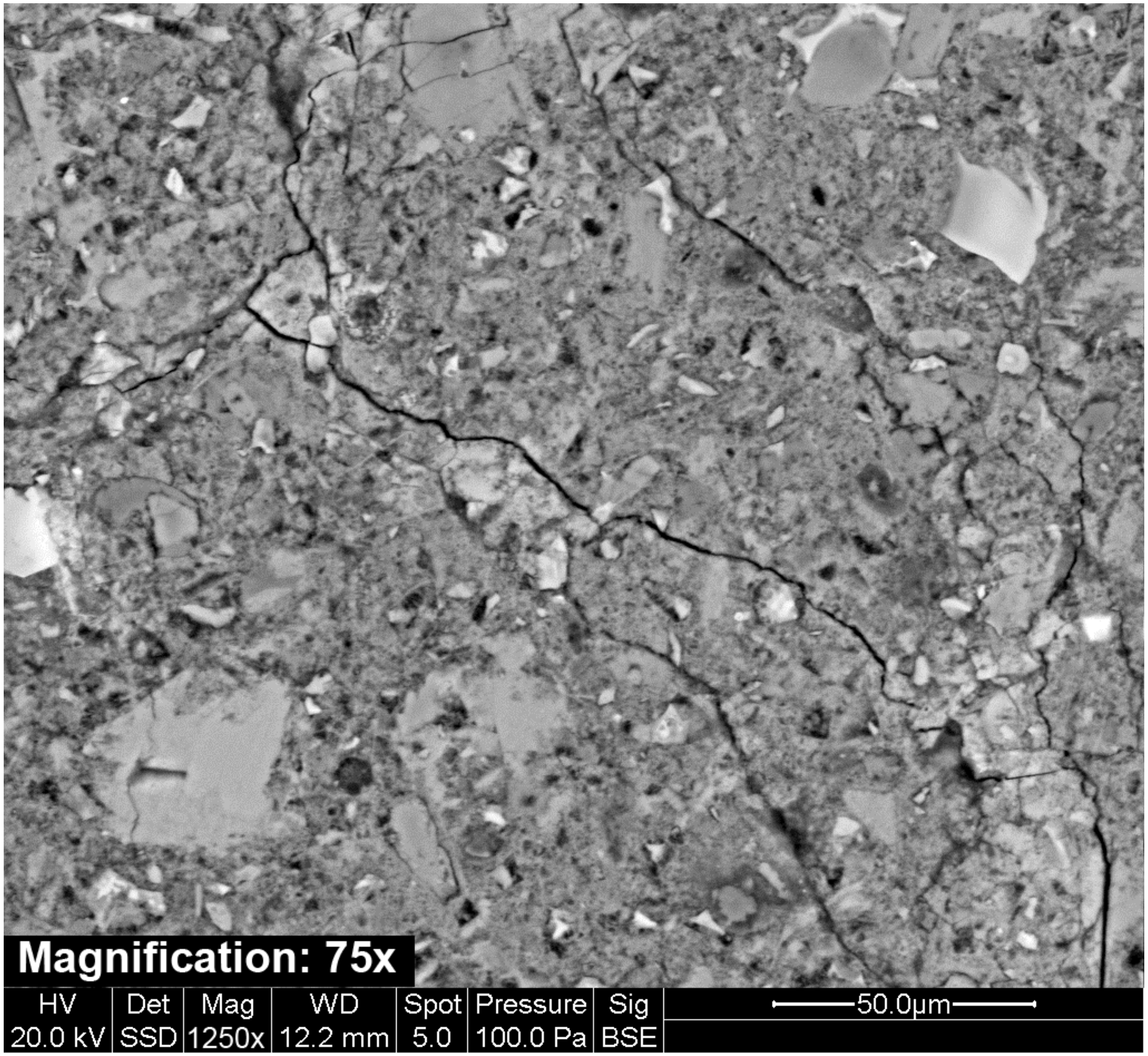
15N (MRS3) Field-Sawn Specimen



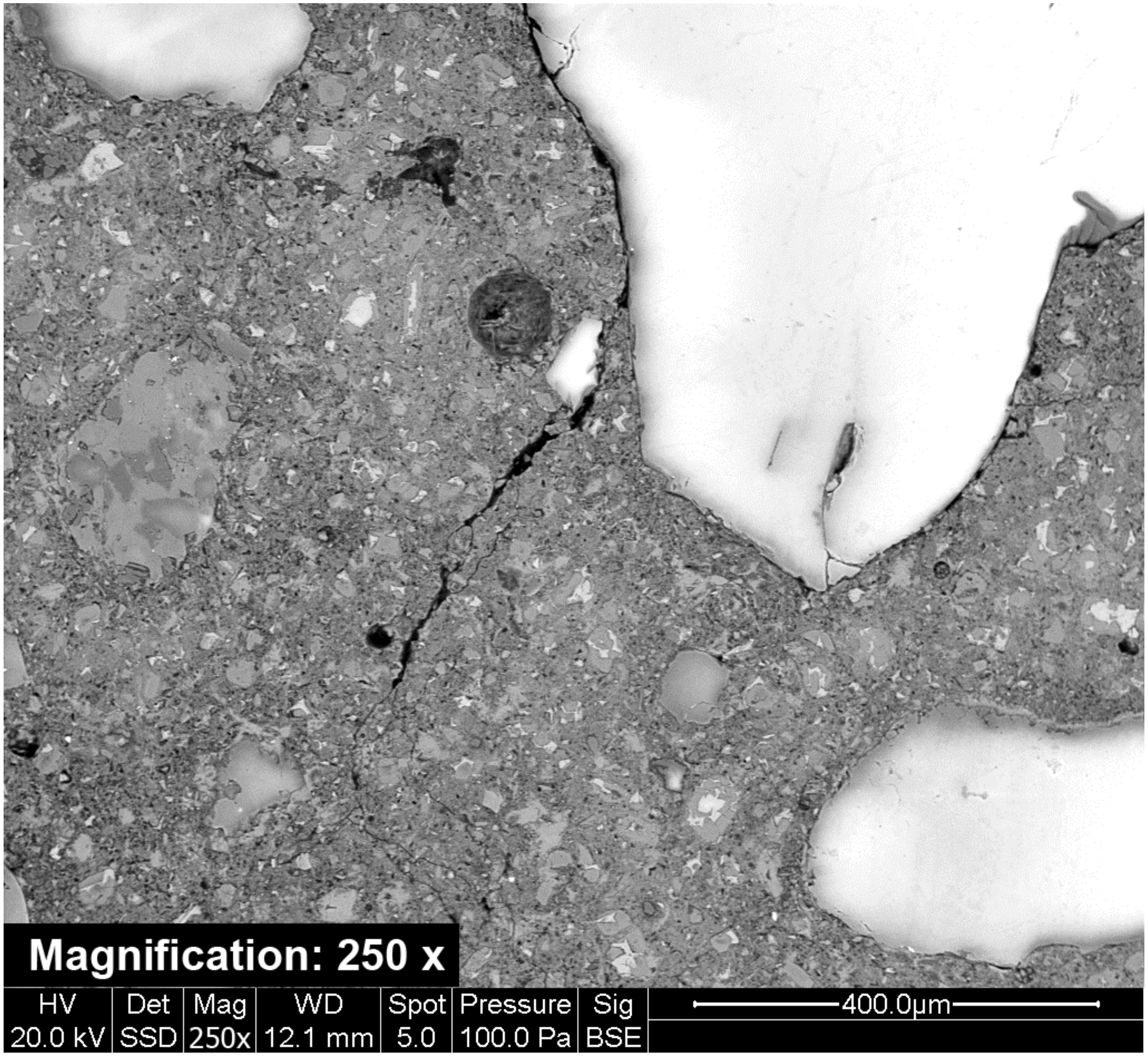
15N (MRS3) Lab-Cured Specimen



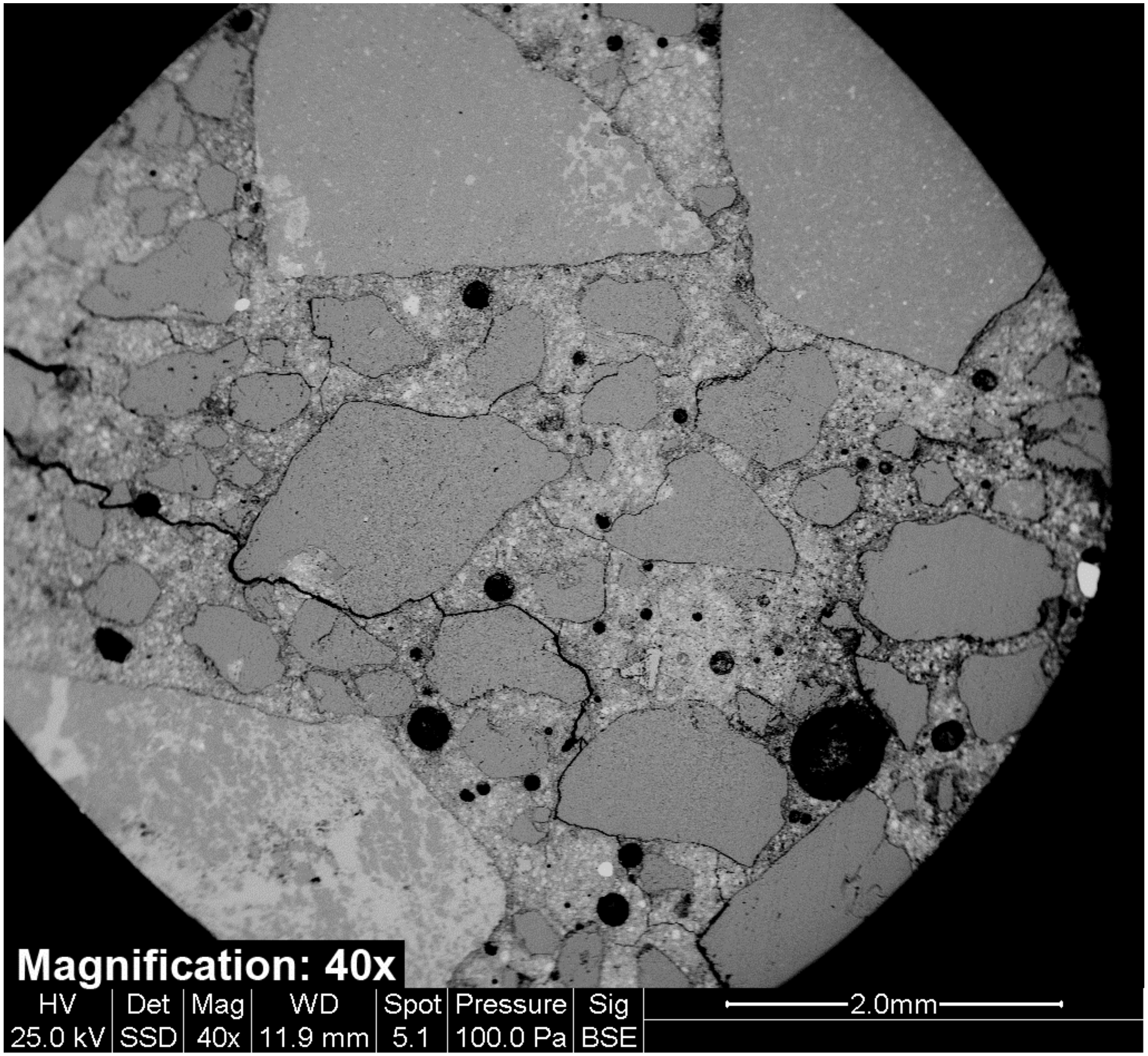
15N (MRS3) Lab-Cured Specimen



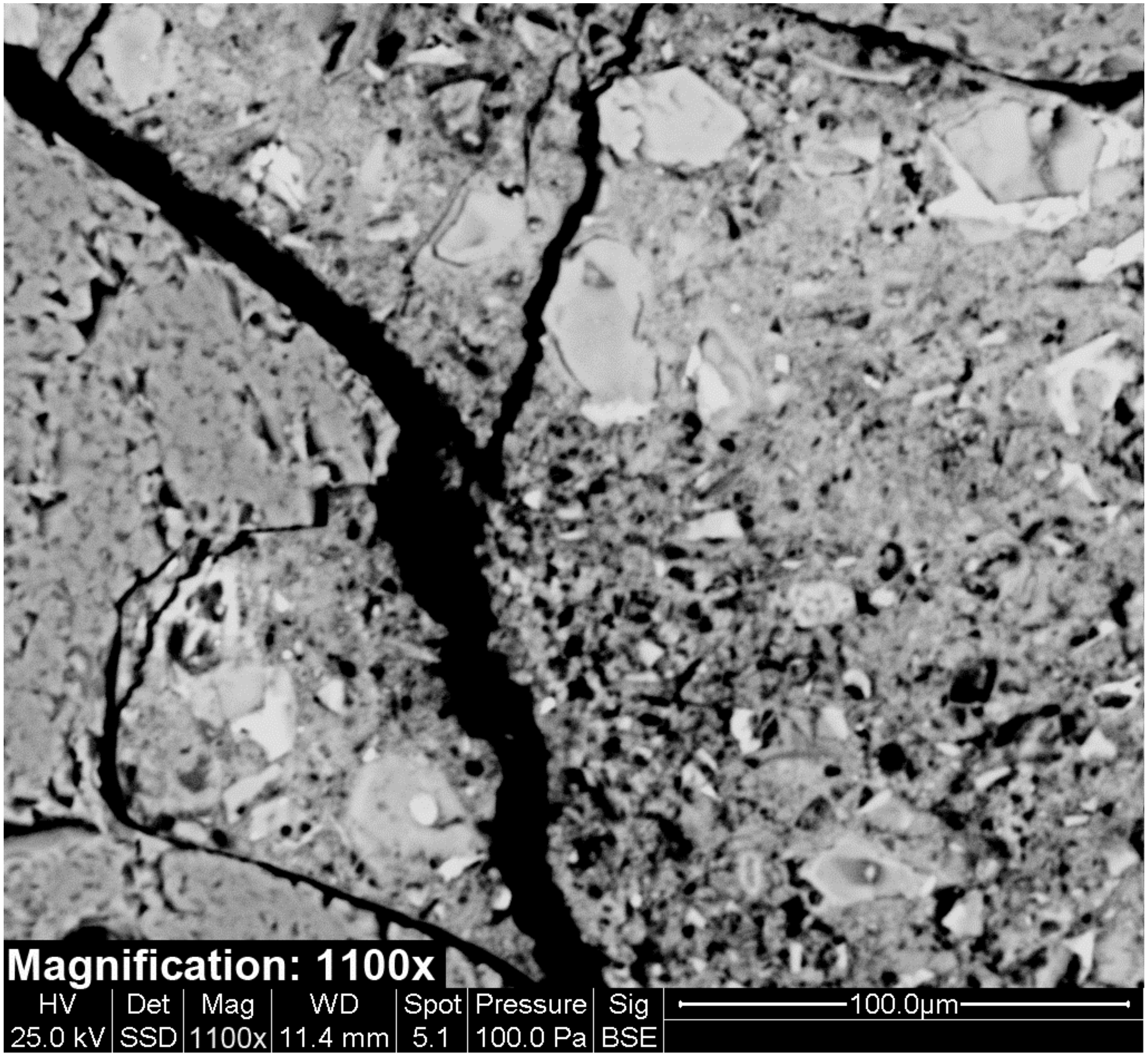
15N (MRS3) Lab-Cured Specimen



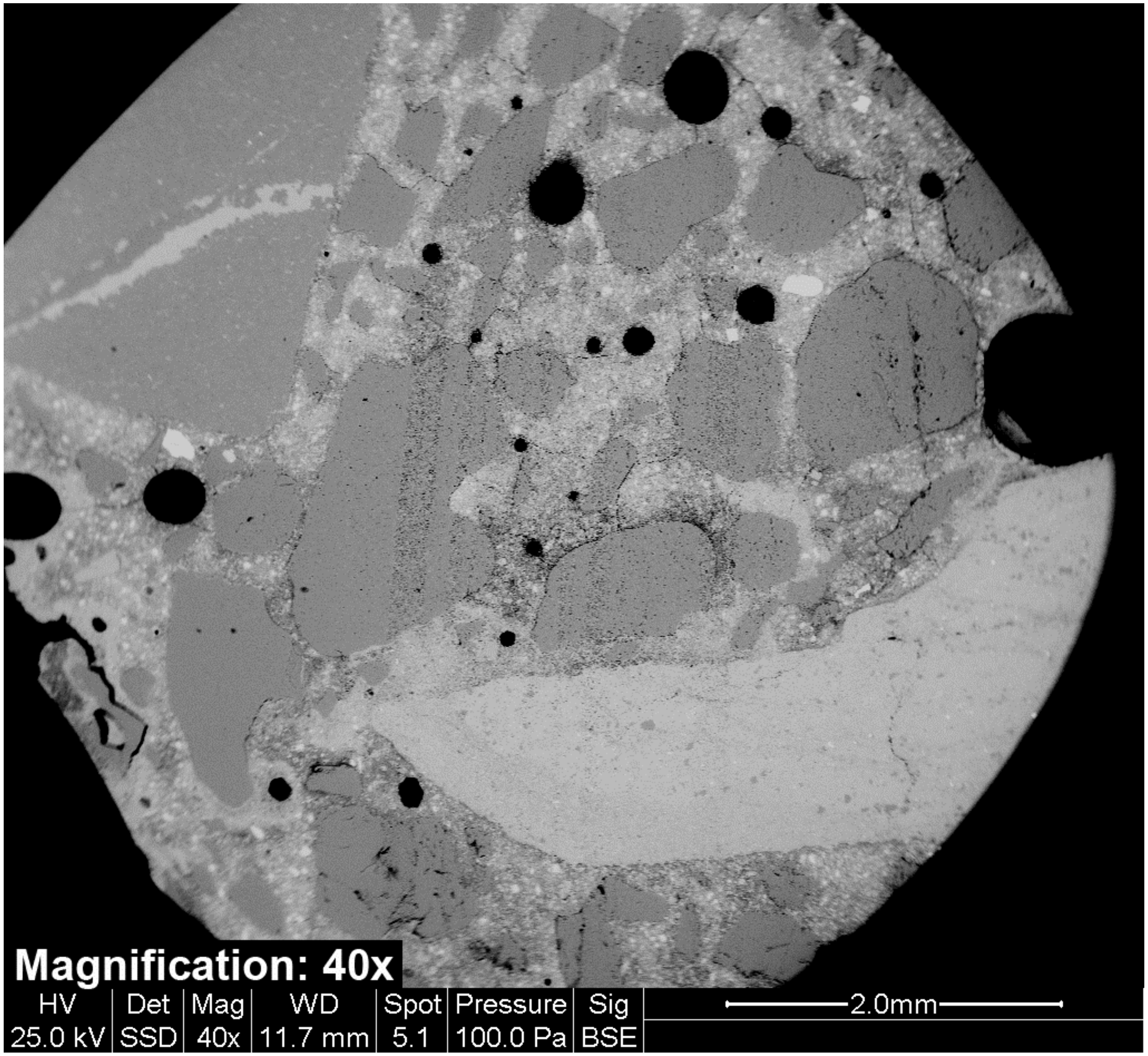
17N (MRS3) Field-Sawn Specimen



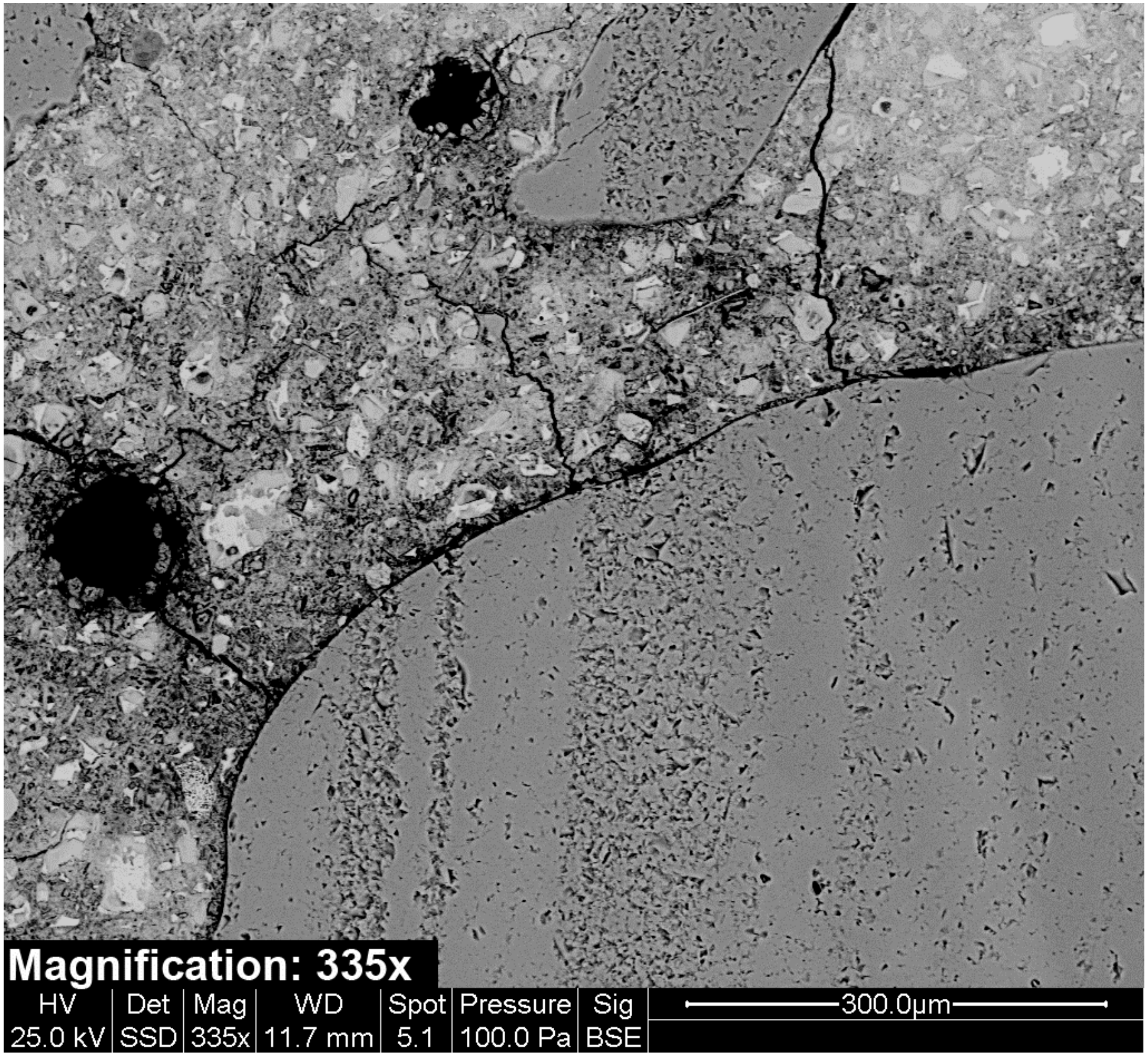
17N (MRS3) Field-Sawn Specimen



17N (MRS3) Lab-Cured Specimen



17N (MRS3) Lab-Cured Specimen



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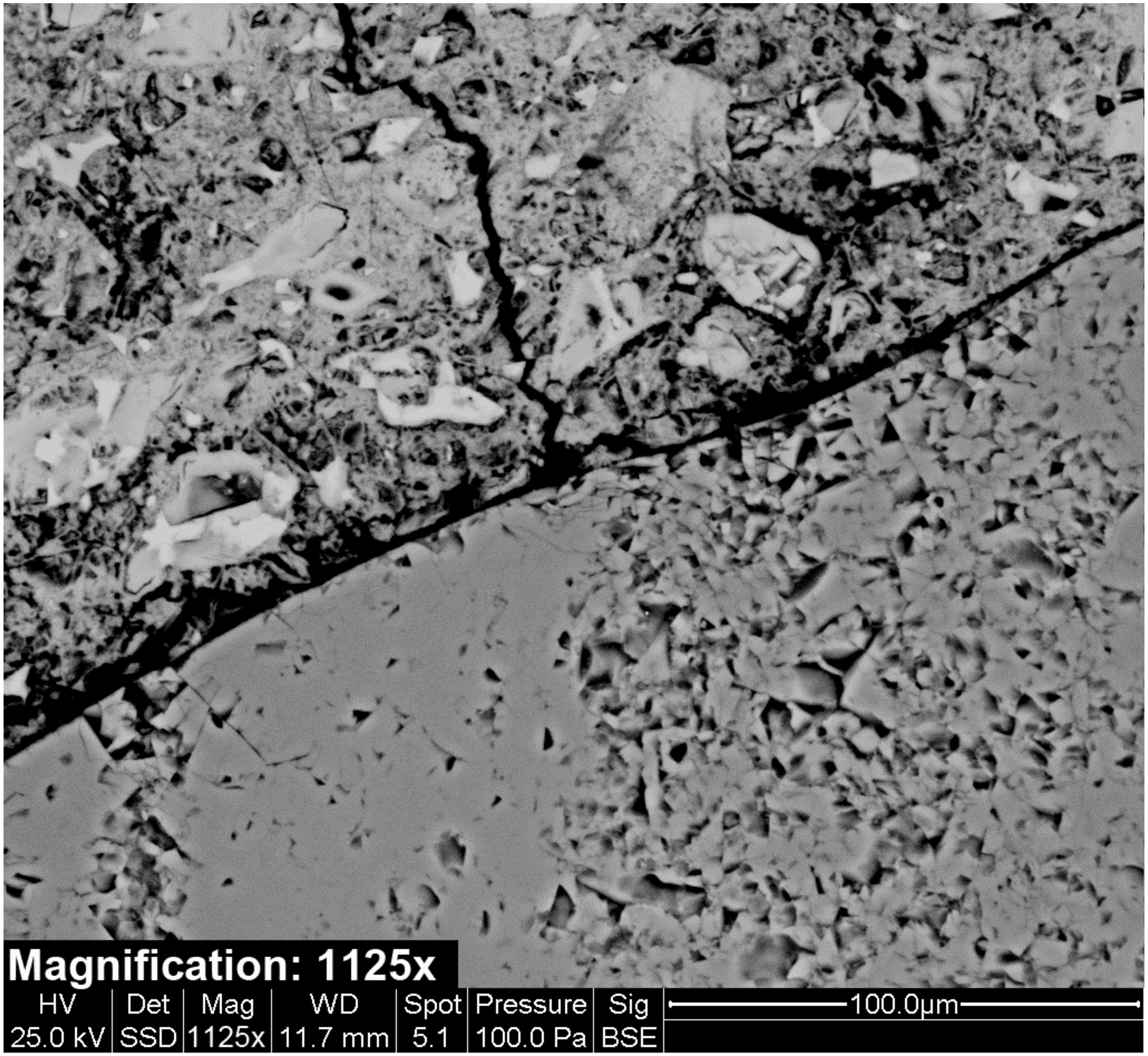
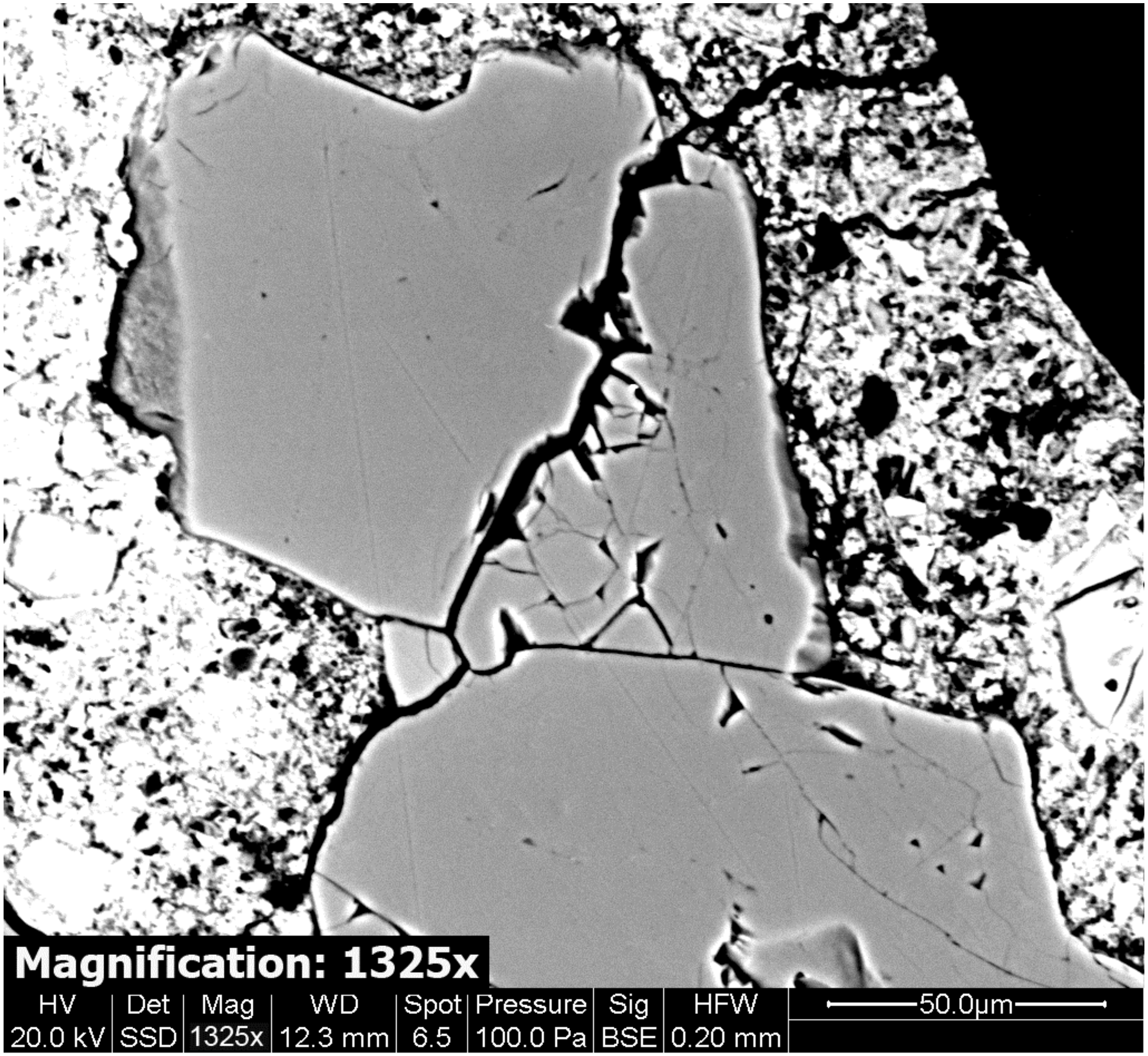
17N (MRS3) Lab-Cured Specimen



Aggregate Cracking Field-Sawn Ambient-Cured



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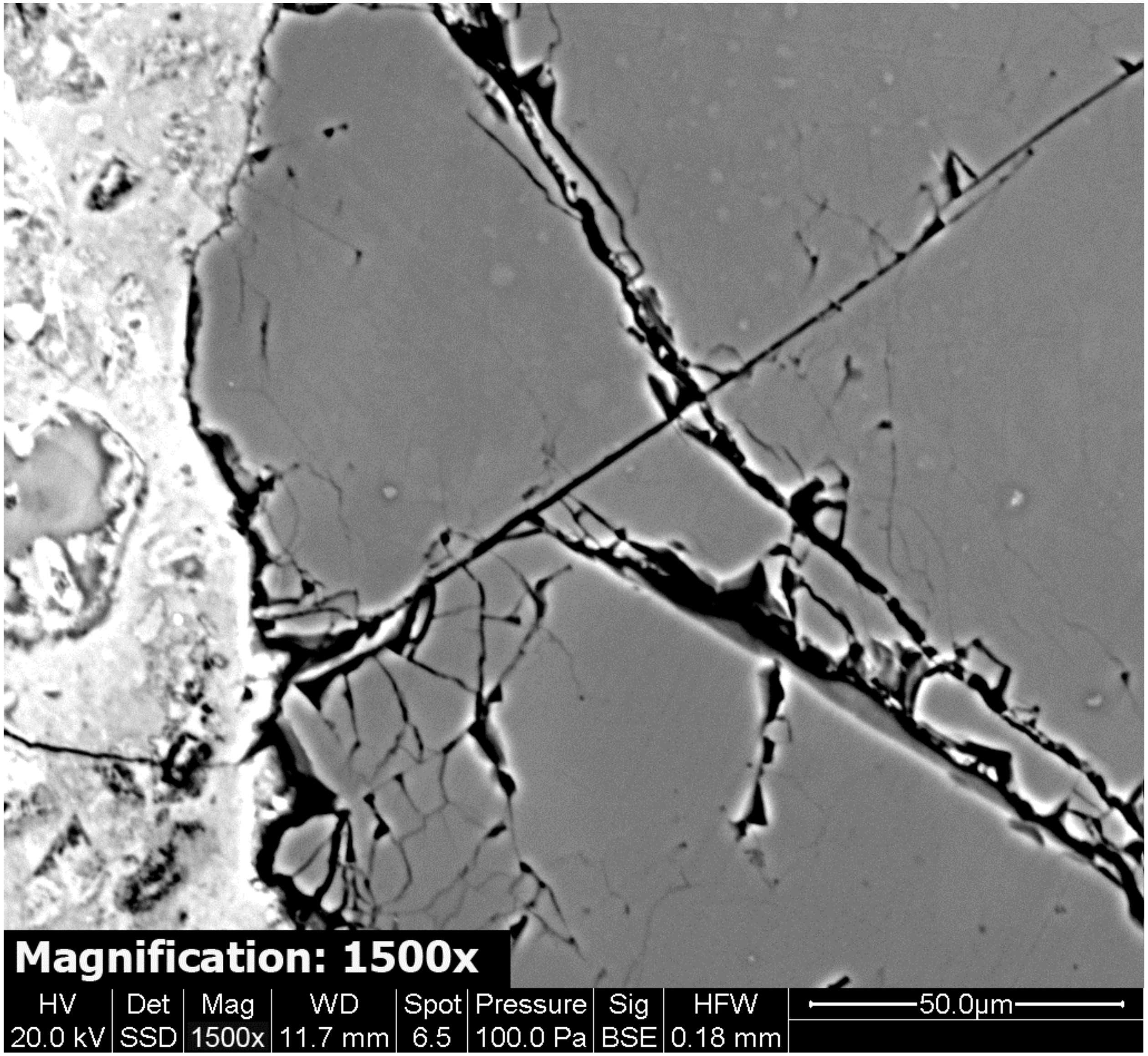
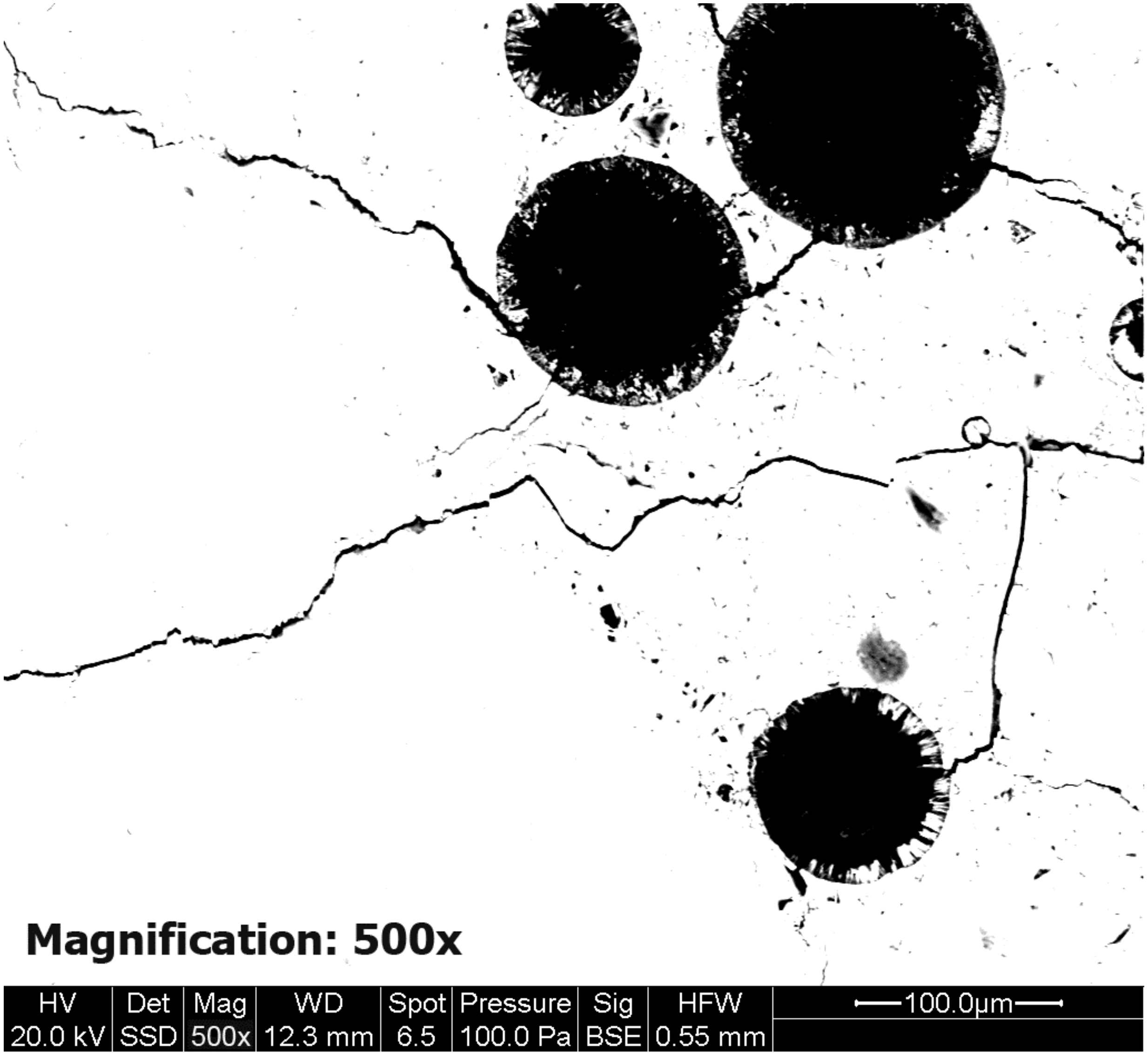
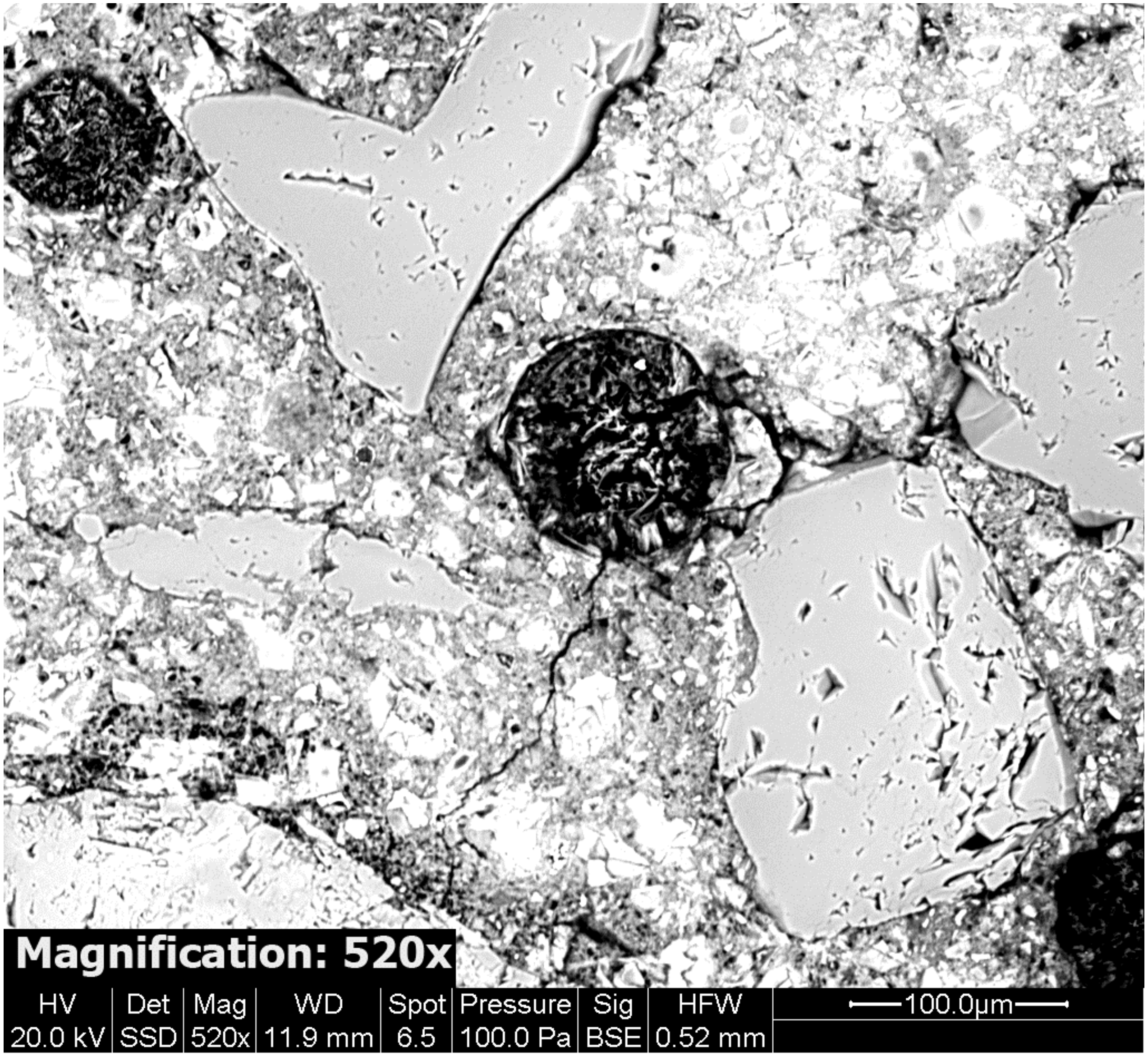
Aggregate Cracking Field-Sawn Long-Cured



Ettringite Field Sawn Ambient-Cured



Ettringite Field Sawn Long-Cured



Summary of SEM Observations

Location	Slab	Type	Observations
MRS2	29N	Lab-cured (beam)	• Ettringite formation • Very few apparent pores
MRS2	29S	Field-sawn (beam)	• Ettringite formation • Significantly larger pore space distributed throughout the specimen
MRS3	15N	Lab-cured (beam)	• Similar Si and Ca content in EDS analysis • Voids of different size distributed throughout the specimen
MRS3	15N	Field-sawn (cylinder)	• Ettringite formation • More pores compared to lab-cured specimen
MRS3	17N	Lab-cured (cylinder)	• Similar Si and Ca content in EDS analysis • High amount of pores
MRS3	17N	Field-sawn (beam)	• Similar Si and Ca content in EDS analysis • Higher amount of pores compared to lab-cured specimen
MRS2	13N	Field-sawn (beam-ambient stored)	• Ettringite Formation
MRS2	13N	Field-sawn (core-controlled curing)	• More Ettringite formation compared to ambient-stored specimen • Possible ASR in cracks based on EDS

SUMMARY

- Fracture & fatigue relationship is completely confounded with flexural strength, since one mix at each strength level tested
- Fracture energy results of lab-cured beams high given the NAPTF modulus of rupture results; possible effects of transport and different storage?
- No direct observations and little evidence of ASR; evidence of delayed ettringite formation

Acknowledgements

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